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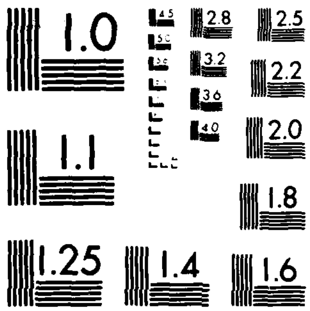

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US Army Corps of Engineers

TECHNICAL REPORT S-71-6

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ENGINEERING PROPERTIES OF CLAY SHALES

Report 5

STRENGTH AND DEFORMATION PROPERTIES OF PEPPER AND DEL RIO CLAY SHALES FROM WACO DAM

by

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This report presents results and analyses of laboratory tests which were conducted on structured to slightly structured, uncemented to slightly cemented clay shale foundation materials from the foundation strata of Waco Dam, Waco, Tex. These materials are commonly called "clay shales" and have properties more nearly those of soil than rock. The investigation was conducted for the purpose of determining the effect of current (1962-1969)

(Continued)

20. ABSTRACT (Continued).

standard soil testing techniques on the shear strength values of clay shales. The effects of variations in the rate of strain, specimen size, and length of shear path in the direct shear tests were studied. Results indicate that the shear strength increases as the specimen thickness and the rate of strain decreases.

Consolidation test results show no effects from use of different inundation liquids, no evidence of structural collapse, and no differences in side friction under various ring preparations. Values of t_{50} and expansion pressures were different for the specimens of various thicknesses, but causes of these differences are not apparent.

Results of triaxial compression tests indicate a significant amount of negative pore pressure in the laboratory specimens. It must be assumed that the negative pore pressure developed after the samples were obtained since the materials in situ exhibited pore pressures in excess of the ground-water table.

The variation in physical properties of the undisturbed test specimens, such as density, water content, plasticity, and structure, contributed appreciably to variations in all test results.

Results of this study indicate the need for new test procedures and equipment to determine the shear strength characteristics of clay shales. Additional research is required to develop the most applicable techniques.

PREFACE

The U. S. Army Corps of Engineers has had a long and continuing interest in construction and maintenance problems associated with clay shales. This interest exists primarily because of the special slope stability problems encountered with these materials and their extensive occurrence as foundations beneath structures and embankments. In 1961, a major slide in the clay shale foundation during construction of Waco Dam focused new emphasis on these problems. To understand more fully the engineering properties and behavior of these materials, laboratory investigations were authorized by the Office, Chief of Engineers (OCE), U. S. Army.

The U. S. Army Engineer District, Fort Worth (FWD), initiated laboratory investigations (1961-1963) in conjunction with the reanalysis and reconstruction following the slide in Waco Dam. The District expanded these investigations under Engineering Study (ES) 529, "Shear Strength Characteristics of Clay Shale Foundations" (1962-1969). The laboratory testing for both investigations was performed by the U. S. Army Engineer Southwestern Division Laboratory (SWDL).

The U. S. Army Engineer Waterways Experiment Station (WES) conducted Engineering Studies under ES 529 and ES 542, "Engineering Properties of Clay Shales" (1968-1974). These investigations were expanded under the Civil Works R&D Soils (311) Program Work Units 31151, "Engineering Properties of Clay Shales" (1975-1978), and 31244, "Strength and Deformation Properties of Clay Shales" (1979-present).

The research results have been documented in the following technical reports in the series, "Engineering Properties of Clay Shales": Report 1, "Development of Classification Indexes for Clay Shales," June 1971; Report 2, "Residual Shear Strength and Classification Indexes of Clay Shales," August 1974; Report 3, "Preliminary Triaxial Test Program on Taylor Shales from Laneport Dam," September 1976; and Report 4, "Laboratory and Computational Procedures for Prediction of Pore Pressures in Clay Shale Foundations," September 1982.

This report, Report 5, "Strength and Deformation Properties of Pepper and Del Rio Clay Shales from Waco Dam," documents an investigation initiated under ES 529 to detect and evaluate the effect of testing techniques on the strength values of clay shales. The study also addresses the difficulty of

correlating results of laboratory tests on clay shales with the in situ behavior. The laboratory test data on the Pepper and Del Rio clay shales from the foundation of Waco Dam are documented in Appendix A. Part II contains comments on the laboratory testing authored by Mr. Arthur H. Feese (SWDL) who directed the development of laboratory equipment and test procedures used in the research. Part I, authored by Mr. William R. Stroman (FWD), contains an engineering analysis of the test data with particular emphasis on application to construction and performance of Waco Dam prior to 1969.

The report was completed in 1969 as an internal reference by the FWD. During 1983, the unpublished data were used by WES in support of the Civil Works R&D Work Unit 31244 in conjunction with additional research tests on Pepper clay shale sampled in January 1983 by FWD during piezometer installations at Waco Dam. The report was also reviewed in light of current state-of-the-art technology by OCE, SWD, FWD, WES, Consultant R. R. W. Beene (retired, FWD and OCE), and the authors. These reviews were taken into account by the authors during preparation of this report for publication in support of current research by WES and studies by the FWD for the Embankment Criteria, Performance, and Foundation Report (prepared under Engineer Regulations ER 1110-2-1801, 1901).

During the investigations (1965-1969), Mr. William M. Nichols (deceased, FWD) was a contributor to the analyses. Mr. Charles F. Swenson was Chief, Engineering Division, and COL R. P. West (deceased) was the Fort Worth District Engineer. Mr. Shigeru Fujiwara was Chief, Engineering Division, and COL Theodore G. Stroup was Fort Worth District Engineer during the 1983 studies.

The report was reviewed and published in conjunction with current clay shale research at WES under Civil Works Work Unit 31244 directed by Mr. Clifford L. McAnear, Chief, Soil Mechanics Division. Dr. William F. Marcuson III was Chief, Geotechnical Laboratory. Mr. Fred R. Brown was Technical Director and COL Tilford C. Creel, CE, was Commander and Director, WES.

CONTENTS

* Plates of Appendix A are on microfiche and have been inserted in a pocket at the back of the report.

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
degrees Fahrenheit	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet per mile (U. S. statute)	0.18939	metres per kilometre
inches	2.54	centimetres
miles (U. S. statute)	1.609347	kilometres
pounds (force) per square inch	6894.757	pascals
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
tons (force) per square foot	95.76052	kilopascals

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use $K = (5/9)(F - 32) + 273.15$.

ENGINEERING PROPERTIES OF CLAY SHALES

STRENGTH AND DEFORMATION PROPERTIES OF PEPPER AND DEL RIO CLAY SHALES FROM WACO DAM

PART I: ENGINEERING ANALYSES OF LABORATORY TEST DATA

CHAPTER 1: INTRODUCTION

Purpose

1. Initially a study was proposed to determine the effect of several test methods and procedures on shear values of clay shales. Three variable test procedures were visualized as having an effect on the indicated shear strength: (a) rate of strain, (b) specimen size, and (c) length of shear path. The program was later expanded to include determination of variations in basic properties (moisture content, degree of saturation, and soil indices) and consolidation characteristics derived using different test procedures.

Scope

2. The program consisted of conducting a series of laboratory tests designed to provide information as to the effect of variations in test procedures on two types of clay shales. Variation in test procedures included type of water used in sample preparation and testing, specimen thickness, rates of loading, and minor modification of testing equipment.

Authority

3. Authority to perform these investigations was granted in ENGCW-EC letter dated 1 November 1962, subject: Civil Works Investigations FY 63.

Current (1983) Review

4. **Expansion pressure-values shown on consolidation test void ratio-pressure curves were determined by saturating the sample at the void ratio as**

existing in the laboratory. During the past few years it has become evident that test specimens should first be reloaded to field overburden pressures and then saturated. This test procedure produces significantly higher expansion pressures.

CHAPTER 2: MATERIALS

Source

5. Materials used in this investigation were from the geological formations comprising a portion of the embankment and spillway foundations at Waco Dam, Waco, Tex. Samples used for shear strength, consolidation, moisture content, density, and soil indices tests were obtained from Borings 8A6C-445, -446, and -447 beneath and adjacent to the downstream berm and from Borings DR-1, -2, -3, and -4 in the spillway area. Mineralogical and related identification tests were performed on samples obtained from Borings 8A6C-352 and 8A6C-354 beneath the main embankment. Locations of the borings are shown in Plate 1. Subsurface profiles, indicating the zones from which the samples were obtained, are shown in Plate 2.

Geological History of Materials

Physiography

6. Waco Reservoir lies within the Bosque River drainage system. The confluence of the North, Middle, and South Bosque Rivers occurs under old Lake Waco, approximately 1 mile* upstream from the new dam axis. Old Lake Waco Dam was located about 2,000 ft upstream of the new dam and is now inundated by the new reservoir. The main stem of the Bosque River empties into the Brazos River approximately 4 miles downstream from the new dam. The reservoir topography consists of rolling plains incised, to varying depths, by the three forks of the Bosque River and their tributaries. Bosque River terraces occur as high as 120 ft above the present North Bosque River channel. The North Bosque is incised approximately 30 ft into a broad (as wide as 4,000 ft within the reservoir area) floodplain valley which, in turn, is incised from 100 to 150 ft below the upland plains. The Middle Bosque River is incised to depths of 10 to 20 ft into a poorly developed floodplain valley, which is in turn incised to depths of 70 to 80 ft below the upland plains. The South Bosque River flows against the Bosque escarpment on its south or right bank and is

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 5.

incised to depths of from 70 to 80 ft below the upland plains on its north or left bank. This double incisement of the Bosque River for considerable depths below its earlier terraces indicates multiple degradation, aggradation, and rejuvenation. The incised floodplain of the North Bosque River is better developed because the direction of flow of the North Bosque nearly parallels the dip slope of the rock formations. The direction of flow of the Middle and South Bosque Rivers trends at an angle with and nearly perpendicular to, respectively, the formational dip slope. The Bosque escarpment marks the southwestern limits of the Bosque River drainage system. The escarpment was developed by the down faulting of erosion-resistant Austin chalk, forcing the South Bosque River to erode perpendicularly to the formational dip slope on less resistant shales of the Del Rio, Pepper, and Eagle Ford formations.

Stratigraphy

7. The geologic formations occurring in the area range from the Lower Cretaceous limestones of the Georgetown group to the Upper Cretaceous Austin chalk of the Gulf series. The relative position and thickness of each of the geologic formations encountered in this area is shown in Plate 3. This information was compiled from numerous boreholes which were drilled for the design of new Waco Dam. The stratigraphic position of the various zones of Pepper and Del Rio shales which were used in the tests conducted for this investigation are shown adjacent to the rock column. The two formations pertinent to this report are described in detail below.

8. Del Rio shale. The Del Rio is a soft, calcareous, medium- to thick-bedded, fossiliferous, nonfissile, medium gray to greenish-gray clay-shale. It contains occasional marly, highly calcareous zones and argillaceous limestone seams; occasional thin, disclike, poorly developed clay-ironstone concretions near the base; and occasional thin, softer, dark gray to black shale seams. The Del Rio shale is remarkably homogeneous, with only three identifiable persistent marker horizons. These markers are a thin (0.05- to 0.20-ft-thick), tan-white bentonite seam approximately 3 ft from the top; and two marly, more calcareous horizons, approximately 18 and 22 ft above the base. Calcareous clay-ironstone concretions are found in the upper 25 ft of the formation, and occasional thin (0.1- to 0.5-ft-thick), lenticular limestone beds occur without continuity throughout the section. The basal contact has been placed 0.5 ft below a marly limestone bed about 0.8 ft thick. The top of the Del Rio is marked by an erosional unconformity. The hiatus was of unknown duration, but

time and exposure were sufficient to remove the Buda limestone formation of unknown thickness that had originally overlain the Del Rio. The residual detritus, consisting of fossil shell and fish fragments, sand, lime and shale pebbles, and small phosphatic nodules, has been lime cemented into a conglomerate varying from 0.10 ft to more than 1 ft (infrequently) in thickness. Secondary marcasite is present throughout the Del Rio in nodular form and as fossil replacement.

9. The thickness of the Del Rio varies along the erosional surface, and has been logged from 64 to 72 ft thick. It apparently thins toward the southeast, or in the direction of the right abutment.

10. The Del Rio shale is moderately susceptible to weathering. During construction at Waco Dam, fresh-cut faces of Del Rio shale deteriorated rather rapidly when exposed to atmospheric conditions. On surfaces that have been exposed for some time, even with a protective overburden mantle, the Del Rio shows extensive weathering near the surface. Significantly, the weathering processes penetrate farther along bedding and fracturing than across them. At locations where a broad, flat surface is exposed, oxidation and leaching penetrated only about 1 ft. Iron oxidation is intense, and the lime-bonded clay particles evidently break up into clay particle aggregates, which appear somewhat like silt when moistened. Moderate staining penetrated fairly deep into vertical joints with considerable iron oxidation. Del Rio samples for testing were obtained from the unweathered zone below the bottom of the spillway channel as shown in Plate 2.

11. Pepper shale. The Pepper shale is the equivalent of the upper portion of the Woodbine group at the damsite. It is a soft, noncalcareous, thin- to medium-bedded, fossiliferous, fissile, black compaction shale with occasional beds of hard, nodular claystone, siltstone, and sandy seams. Although the Pepper shale has not been geologically subdivided, test results show a distinct difference in the upper and lower sections of the formation; therefore, for this investigation, the designations Upper Pepper and Lower Pepper have been used. Detailed analyses indicated that the Upper Pepper could be further subdivided into two separate materials, as will be discussed later.

12. The Pepper shale is only mildly susceptible to chemical weathering. On flat surfaces only a thin, 0.2- to 0.4-ft, veneer of chemically weathered shale was found covering unweathered shale. Chemical weathering and oxidation penetrated somewhat deeper along bedding planes and joints. Occasionally,

near the surface siltstone interbeds were found to be highly oxidized while the shale above and below remained almost unchanged. This condition was found for as much as 6 ft below the surface of the Pepper, and probably is closely related to jointing, which would allow the entrance of ground water. Iron oxidation in the form of limonite and hematite is intense only when related to the interbeds; however, jarosite or melanterite (sulfate of iron) is common on exposed Pepper surfaces. Mechanical weathering of the Pepper shale is very rapid; however, when covered by a mantle of overburden and a thin veneer of weathered shale, the Pepper stays intact. Upon removal of the protective cover, it gives up moisture readily and deterioration is rapid. This slaking process extended to more than 3 ft below the surface in places where the Pepper was exposed to atmospheric conditions. A vertical face of Pepper shale deteriorates rapidly. In as short a period as 1 day, vertical exposures of Pepper have been observed to start spalling or slaking, and alternate wetting and drying accelerates the slaking process. On flat surfaces, Pepper shale that has been dried and moistened a few times deteriorates to a mass of small shale fragments. Even the slightest distortion or disruption of bedding greatly accelerates mechanical weathering on exposure. It is significant that no intense weathering is noted on distorted or disrupted bedding that has not been exposed to the air or to surface water.

Structural geology

13. The structural features in the area are related to, or controlled by, the tectonic movements which created the Balcones fault zone. A brief preface to the geologic history is necessary to discuss the Balcones faulting itself. During Paleozoic time, sediments were being accumulated in the Llanoria geosyncline, a relatively narrow trough which is associated with the Ouachita geosyncline and Ouachita synclinorium to the northeast. The sediments for this deposition were derived from the ancient Llanoria land mass to the southeast. During late Paleozoic time, strong orogenic movements obliterated the geosyncline. The sediments were metamorphosed, tightly folded, and subjected to overthrusting to the northwest. Uplift, coupled with this deformation, forced late Paleozoic deposition farther west, placing a relatively thin veneer of sediments on the early Paleozoic and pre-Cambrian basement rocks. In early or mid-Mesozoic the peneplained Llanoria land mass began to subside, reversing the direction of drainage from the northwest to the southeast. This created the following structural condition:

a. A subsiding paleoplain of basement rocks and deposition of early Mesozoic sediments to the southeast.

b. A relatively narrow, thick, orogenically disturbed belt of Paleozoic geosynclinal metamorphosed sediments in the vicinity of the project.

c. A stable area of basement rocks with a thin cover of Paleozoic rocks to the northwest.

Extensive invasion by Cretaceous seas loaded the area with progressively greater increments of sediments to the southeast. Subsidence remained strong to the southeast and relatively minor north of the geosynclinal area. Late Cretaceous was marked by uplift and sea retreat. The Tertiary was marked by repeated attempted sea encroachment. Near balance occurred, with sediment-laden rivers constructing deltas as the sea attempted to encroach overland. This resulted in continued subsidence with tremendous thicknesses of sediments deposited in the coastal plain area. In effect, a hinge was created. The leaf to the northwest was rigid and remained at essentially the same elevation. The leaf to the southeast was relatively rigid and pivoted downward. The hinge proper was the weaker, structurally disturbed, geosynclinal sediments. Extensive normal faulting occurred in the hinge area, developing the Balcones fault zone. The fault zone in this area consists of a complex system of normal faults in a generally en echelon pattern, striking northeast. These faults dip both northeast and southwest. Numerous grabens and horsts occur within the zone. In the Waco Dam area the fault zone is approximately 15 miles wide and its northwest limit trends through the damsite. Dip of the rocks, northwest of the zone, is about 25 ft/mile to the southeast. In the fault zone the dip varies, but averages 50 ft/mile to the southeast. Total throw in the zone is approximately 600 ft, of which about 250 ft occur in three faults or fault zones at the damsite. Warping and dragging of the beds occur adjacent to fault planes. The first development of the Balcones fault zone probably occurred during late Cretaceous, and the most recent major movement took place no later than Pliocene time. Although, in a geologic sense, the Balcones system may still be active, no evidence indicates recent movement in the Waco area. Location of the faults at Waco Dam is shown in Plate 1.

14. Slickensides are common throughout both the Pepper and Del Rio formations, although they are more prevalent in the Pepper. Generally, the slickensides are considered to be a product of faulting, but many can also be attributed to differential compaction of the shales. The Pepper shale in the

CHAPTER 3: ANALYSES AND DISCUSSION

Identification Tests

General

17. Although the materials used in this investigation have many of the properties normally attributed to soils, their geological history and the environment under which they have existed combine to remove them from this strict category. The materials comprising the Pepper and the Del Rio could be assigned into several classifications and groupings. For simplicity both the materials are called "clay shale" because they disintegrate into a claylike mass within a short period of time on exposure to the atmosphere. The Pepper is probably a true "compaction" shale, but the Del Rio, because of its calcium carbonate content, could be classified as a lightly cemented shale. However, the reaction of the Del Rio materials to slaking in water and degradation in atmospheric conditions indicates that strong cementation does not play a major role in the makeup of its structure.

18. During the investigation of the failure of the Waco Dam, it was determined that the Pepper formation consisted of two identifiable zones. Numerous borings and tests indicated that the contact between the two zones occurred approximately 27 ft above the Del Rio-Pepper contact. It was natural to call these two zones the Upper and Lower Pepper. This division was made on the basis of moisture content and density and upon visible characteristics. In analyzing the results of tests conducted for this investigation, it was noted that some of the tests on the Upper Pepper did not correlate. Further investigation into the basic properties showed that the Upper Pepper consists of at least two additional submembers, readily identifiable by differences in the Activity Indices of the respective zones (Seed, Woodward, and Lundgren 1964). In this report the Upper Pepper material is divided into zones having "high activity" and "low activity" colloids. For the purpose of correlating basic properties and delineating the various zones in the Pepper shale, the Del Rio-Pepper contact was chosen as the datum. The contact between the zones of high and low activity has been identified as approximately 40 ft above this datum.

Mineralogical tests

19. Mineralogical tests were conducted on samples from Borings 6DC-352

and 6DC-354. Moisture content and limits tests were conducted on companion samples. Results of the tests are shown in Plate 4. Also shown in this plate are the respective zones from which samples were obtained for strength and other tests. Montmorillonite, illite, and kaolinite were found to be the principal clay-forming minerals. Pepper shale was found to have considerably more montmorillonite than the Del Rio, and the Upper Pepper contained slightly more montmorillonite than the Lower Pepper. Samples of Lower Pepper were found to contain significantly more illite than samples of Upper Pepper. The influence of combinations of illite and montmorillonite on properties of prepared materials has been documented by Seed, Woodward, and Lundgren (1962) and others. This influence on naturally occurring materials has not been investigated, and the results presented here are not sufficient to even suggest what could be expected except that, with an increase in montmorillonite and decrease of illite, the activity index appears to increase.

Moisture contents

20. Moisture content and density tests were conducted for each entire sample and for each individual undisturbed test specimen cut from each sample. The number of individual moisture content tests, the range, and average values are shown in Table 1. Distribution of average moisture in the Pepper shale with respect to distance above the Del Rio-Pepper contact is shown in Plate 6. Except for one sample, the Upper Pepper shows a uniform occurrence of moisture. Eliminating the highest and lowest test values, the entire range of moisture content varies from 19.0 to 21.8 percent. The moisture content range for the zone of high activity is from 19.0 to 20.6 and that for the zone of low activity is from 21.0 to 21.8. The Lower Pepper shows a wider range in natural moisture content than the Upper Pepper. Eliminating the highest and lowest values, the range for the Lower Pepper is from 21.5 to 28.2. By the same procedure, the moisture content range for the Del Rio is from 16.0 to 22.8. It is considered that the Upper Pepper should give the most consistent test results because the gross physical characteristics of the individual test specimens are closer to the overall characteristics of the material.

21. All moisture contents were determined by drying the materials in a forced draft oven at 105° C. Grim (1953) states that this temperature is sufficient to almost completely remove the interlayer water from (dehydrate) montmorillonitic clay particles. This lends some confusion as to the meaning of moisture content and, if bonded water has a density greater than 1.0 as some

observers contend, would account for percentages of saturation in excess of 100 as shown for some of the physical test results. The effect of using high temperatures in other identification tests is discussed in subsequent paragraphs.

Grain-size analyses

22. Specimens for grain-size analyses were oven-dried to 105° C and 50-g portions were slaked in distilled water for 24 hr. None of the materials slaked completely, and dispersion was accomplished with a blender. The specimens were washed into standard hydrometer jars, and 10 mℓ of a stock solution of a buffered calcium hexametaphosphate believed to contain other phosphates in various amounts was added to prevent flocculation. Hydrometer readings were taken at 1, 5, 30, and 120 min and at 24-hr intervals after dispersion. Grain-size distribution curves were developed from the test results. Percentages smaller than selected particle sizes are shown in Table 1.

23. In addition to the more or less standard test, one shale sample was subjected to special investigation to determine the effect of sample preparation and additives on test results. Samples of Upper Pepper, from a depth of 31.5 to 32.4 ft in Boring 8A6C-446 which had been dried to 105° C and which had not been subjected to drying, were tested using three different deflocculants. Results of the tests are as follows:

	Percent Colloids (0.002 mm)	
Deflocculant	Dried to 105° C	Natural Moisture
Calcium hexametaphosphate	44	33
Sodium tripolyphosphate	42	35
Sodium hexametaphosphate	44	35

24. The effect of drying the specimens prior to the test had a more pronounced influence on the test results than the ion exchange capacity of the additive. It should be noted that sodium or perhaps phosphorous is the most probable exchangeable ion available. Since the ground water contains an overwhelming percentage of sodium and potassium as compared to calcium and the other exchangeable ions, it is concluded that no ion exchange could be expected. It is not known what effect, if any, would have been observed if the additive had contained calcium ions available for exchange. Drying the sample to 105° C had a considerable effect on the measured amount of colloids. As stated above, this temperature has been cited as sufficient to remove almost

completely the interlayer water. This would, in effect, reduce the particle size. Grim (1953) states that montmorillonite rehydrates easily unless all the water is removed from between the soil plates. However, the 24-hr slaking (rehydration) period allowed before conducting the test is possibly not sufficient time to allow for complete rehydration.

Atterberg limits tests

25. Specimens for Atterberg limits tests were covered with either distilled water or ground water without the samples having been subjected to artificial drying and slaked for at least 24 hr. The material was then processed in a blender. Excess water was removed by absorption in plaster of paris bowls. Liquid limit tests conducted in the early stage of this program (samples from Borings 445 and DR-1, -2, and -4) were conducted by the simplified (one-point) method. Samples tested later (Borings 446 and 447) were tested by the four-point method. Values for liquid limits and plasticity indices are given in Table 1. Figure 1 of Plate 5 shows a plot of liquid limit versus clay content, and Figure 2 of Plate 5 shows the relation of the liquid limit versus plasticity index with respect to the "A" and "U" lines. Results of limits tests with respect to Del Rio-Pepper contact are shown in Plate 7.

26. Three tests were conducted on materials which had been dried to 105° C prior to testing. Duplicate tests were conducted on material from the Lower Pepper which had been prepared at both natural moisture content and after drying to 105° C. These tests indicate a significant increase in the liquid limit value due to oven-drying and showed a change in liquid limits from 78 to 95 percent. Tests on oven-dried material from the Upper Pepper and the Del Rio did not have duplicate tests conducted on material which had not been dried.

27. As stated above, a number of limits tests were conducted using ground water as the preparation fluid. Analyses presented in Table 2 show that the ground water contains considerably more sodium and potassium than either calcium or magnesium. The effect on test results using water with more calcium and magnesium ions is not known. Tests using ground water showed a slight increase in the liquid limit values (averaging approximately 2 percent) over those using distilled water.

Activity index

28. Skempton (1953) proposed an index property for soil which related the plasticity index to the clay fraction. The numerical value of this index was determined by dividing the plasticity index by the percent finer than

0.002 mm. Seed, Woodward, and Lundgren (1962) refined the numerical value to equal the plasticity index divided by the percent finer than 0.002 mm minus a constant. Laboratory tests indicated this constant to be somewhere between 9 and 11. For the purpose of this study, a constant of 10 has been used and the activity index has been determined by the ratio:

$$A_I = \frac{\text{plasticity index}}{\text{clay fraction} - 10}$$

Values of A_I are shown in Table 1.

Consolidation Tests

29. Consolidation tests were conducted on specimens having nominal thickness of 0.25, 0.375, 0.50, and 1.00 in. All specimens were 4.44 in. in diameter. The consolidometer ring was of the fixed-ring type. Drainage was permitted from both the upper and lower sample surface. Results of the consolidation tests, in terms of pressure-deformation curves, are presented in Plates 9 through 12. In these plates the ordinate indicates the average void ratio of the four test specimens and the unit compression (inches per inch) for each increment of load. Along with the pressure-deformation curves is shown the increase in unit compression; that is, the increase in change in void ratio of the three thinner specimens with respect to the unit deformation of the 1.00-in.-thick specimens.

30. The tests conducted on the high activity zone of the Upper Pepper, shown in Plate 9, on the Lower Pepper, shown in Plate 11, and the Del Rio, shown in Plate 12, were conducted in the earlier phase of the testing. The laboratory reported that these tests showed extrusion of material between the consolidometer ring and the upper porous stone. This condition was remedied by application of a circumferential ring of epoxy resin on the porous stone to reduce the clearance to 0.003 in. In addition, the bases of the consolidometers were remachined to assure a more even contact between the specimen and the lower porous stone and between the stone and base. Using the repaired consolidometers, the Upper Pepper was retested. The results of these tests are presented in Plate 10. Results of companion tests, using different saturation fluids, loading times, and using liners, are shown in Table 3. Unfortunately, the specimens were obtained from the zone which showed low activity, so no direct comparison could be made as to the benefit from revising the equipment

used in the test. However, the deformation-reduction curves shown in Plates 9 through 12 do present an interesting comparison of the materials. According to Schmertmann (1955), the deformation reduction curves represent a measurement of the relative disturbance of the thinner specimens compared to the thickest (1.0-in.) specimen. That is to say, the larger the value of deformation reduction for a given load in terms of deformation, the greater the degree of disturbance. This is not to assume the 1.0-in. specimens represent undisturbed tests; only that the thinner specimens are disturbed to a greater degree than the 1.0-in. specimens. As can be seen, the tests conducted on the more precisely fitting consolidation equipment, which should give the more consistent test results, generally show the largest values of deformation reduction, indicating a greater degree of disturbance. This is contrary to what should be expected from the improvements made in the test equipment. It is believed that the disturbance evidenced is from some source other than the extrusion. Possibly it occurs during specimen preparation in the laboratory or from disturbance during sampling operations in the field or both. Whatever the cause, it appears to be more noticeable in the low activity material. This phenomenon will be discussed further in the section on direct shear tests.

31. Another facet of consolidation test results is the differences in expansion pressures exhibited by specimens of different thickness. For some reason not understood, the thinner specimens almost invariably required the lesser load to control expansion. This effects a transfer of the entire e-p curve to the left for the thinner specimens. Again, specimen disturbance could be a factor. There are insufficient data to relate expansion characteristics to activity index, but it can be assumed that the maximum potential expansion pressure probably was not measured in the laboratory because water was used to wash the cuttings from the hole during drilling. The core samples had access to the wash water and, although the permeability of the materials is very low, they could have absorbed an unknown amount of water at that time. This would result in lowering the expansion value which could be measured in the laboratory.

32. Consolidation test data on 1.0-in.-thick specimens for the various materials tested are presented in Plates 13 through 17. These curves represent data which could ordinarily be used in design studies.

33. It could be suggested that none of the tests conducted on the Pepper shale would provide satisfactory answers for problems involving settlement.

Although an apparent virgin compression curve was defined in each test, the indicated maximum past pressures are only a fraction of the value which would be estimated from the geologic history of the area. The test shown for the Del Rio shale indicates somewhat higher maximum past pressure, but the value is still less than what would be estimated from geologic history.

34. On the other hand, the maximum past pressure values from the consolidation test data could possibly be the correct values for use in design. The release of diagenetic bonds during normal degradation of the area in the geologic past could result in a lowering of the indicated maximum past pressures. This could increase the amount of consolidation which would actually occur in a stratum reloaded to pressures less than the effective pressure under which it had once existed. The value of maximum past pressures with respect to hypothesized geological conditions will also be discussed in the following section.

Direct Shear Tests

35. Direct shear tests were conducted on specimens from the Del Rio and Upper and Lower Pepper shales. Specimens were 3.0 in. square and 1/4, 3/8, 1/2, and 1.0 in. in thickness. Test specimens were trimmed into cutters and then placed directly into the shear box, inundated with tap water, and consolidated under 1.5-tsf normal load for at least 16 hr. The normal loads were then increased to the full desired levels, and the specimen was permitted to consolidate for an additional 24 hr. The cutters are split horizontally at midplane which coincides with the plane in the test specimen along which stress is applied. At the start of tests the upper frame of the shear box was raised to a position of 0.05 in. above the lower frame and secured to the piston. The two halves of the cutter containing the test specimen remained in contact along lips having a width of 0.1 in. The shear rate was established to test a set of specimens of each type shale: fast (0.006 in./min), medium (0.00008 in./min), and slow (0.000004 in./min). The rates actually achieved varied somewhat from the above, and are shown along with the rest of the test data in Table 4. The rate of shear was closely controlled during the working day by manual adjustment of variable speed reducers ("Zero-Max") but tended to drift during the night and over weekends, resulting in deviations of some magnitude in some instances. Tests were conducted using normal pressures of 1.5,

3.0, 6.0, 12.0, and 18.0 tsf. Several factors prevented the preparation of all the specimens for a given set at the same time and, in some cases, it was necessary to use specimens from different samples to complete a set. A test was discontinued when failure occurred. Failure was defined by a continuing drop in shear resistance or when the shear resistance remained constant for a long period of time. Final water contents were taken from the centers of specimens after the tests were completed. Results of tests of all direct shear specimens are shown in Table 4.

36. The exact mode of failure in the thinner specimens was difficult to ascertain in most cases. Failure frequently occurred across an edge, in which case the adjacent material was usually soft and mushy and the fractures were ill-defined. Close examination of the 1/4-, 3/8-, and 1/2-in.-thick specimens after testing suggested a trend toward more steeply inclined across-edge fractures as thickness decreased, but the mushiness of the failure zones made it impossible to obtain accurate measurements. The tendency was for the 1-in. specimens to fail along horizontal planes as opposed the across-edge failures of numerous thinner specimens. Based on careful observation, the orientation of failure planes for the various materials and thicknesses are summarized below:

Specimen Thickness, in.	Number of Failures: Across Edge	Number of Failures: Horizontal
	Upper Pepper	
1/4	10	0
3/8	14	1
1/2	6	4
1	1	13
	Lower Pepper	
1/4	10	0
3/8	9	0
1/2	9	3
1	3	9
	Del Rio	
1/4	10	0
3/8	9	0
1/2	10	1
1	0	11

37. As has been previously mentioned, the Upper Pepper appeared to be the most consistent of the three shales tested from point to point with respect to basic properties. Plots in Plate 18 show the results of tests conducted on samples of four specimen thicknesses at medium rate of strain for the zone of high activity Upper Pepper. A reduction in shear strength with reduction of specimen thickness is indicated. Plots in Plate 19 show a similar comparison for the Lower Pepper shale. The data are not so orderly, probably because of variations from specimen to specimen, but the same trend is indicated.

38. The across-edge failures create questions as to the validity of the test data for the thinner specimens since such failures indicate improperly applied shear stresses. It is assumed in the computation of shear stresses that strains and stresses are distributed uniformly over the failure surface. To a great extent this may be true if the shear force is transmitted to the failure plane only through the porous stones at the top and bottom of the specimen. However, the geometry of the ordinary direct shear box restricts uniform straining because of the rigid sides of the box. Hvorslev (1960) presented data indicating that at low strains, the desired condition of uniformity may exist in the central portion of a specimen, but with considerable nonuniformity of strains at both ends. This nonuniformity results from stress concentrations at the contact between specimen and ends of the box. Hvorslev showed, however, that with continued shear displacement, the zones of nonuniformity may propagate inward along planes that are oblique to the preselected failure plane and intersect specimen boundaries at the upper and lower porous stones. Two failure planes then exist, neither of which is the desired horizontal plane.

39. In the case of the brittle materials tested in this program, the strains were much smaller than for a normally consolidated clay, and the strain distribution immediately prior to failure was not known. It is possible that at very small strains all planes are strained uniformly and remain essentially parallel. The across-edge breaks may thus be the same phenomenon as noted by Hvorslev in more plastic soils where the tendency is for failure planes to develop along lines not parallel to the direction of applied force when subjected to large strains. In such a case, measured deformations immediately prior to across-edge fracturing may represent reasonable estimates of shear strength, just as in plastic clays.

40. When plastic clays are tested and the ends of the shear box have begun to cause unequal strains, it is clear that stress concentrations at the

ends make the assumption untenable that unit stress may be computed by dividing force by total area. It appears likely, however, that these concentrations are partially relieved by readjustment of particles, plastic flow, or remolding, thus effecting some redistribution of stress across the full area. The occurrence of this action is to some degree substantiated by the fact that direct shear test results on plastic clays usually check well with the results of triaxial compression tests in which stress concentrations leading to progressive failure are not believed to be a major defect. In such a case, use of the full area of the specimen might lead to only minor errors in strength determination. But with a more brittle, highly structured material such as the Pepper shale, plastic readjustment may be so slow that virtually no relief of stress concentration occurs. If this is the case, the strength values indicated are only relative.

41. Assuming the tests on the 1-in.-thick specimens have some degree of validity, then an interesting comparison can be made between the high activity and low activity zones of the Upper Pepper. As shown in Plate 21, there is a considerable difference in shear strength between the two zones; the low activity zone having the lower strength. This is related to the higher degree of disturbance indicated by the consolidation tests conducted on material from the low activity zone when compared to the tests conducted on the material from the high activity zone, as shown in Plates 9 and 10. As in the consolidation tests, the material from the low activity zone is considered either more susceptible to sample disturbance or to have less capacity for retention of the diagenetic bonds, or both.

42. After eliminating the suspect test results, i.e., tests which showed across-edge failure, and grouping samples having common basic characteristics, a comparison of the effect of rate of shear was made on materials from the high activity zone of the Upper Pepper shale, as shown in Plate 20. Part of these data are also summarized in Table 5. Apparently the cohesion parameter is affected most by the rate of shear, or at least, the slowest rate shows the lowest indicated resistance to shear. Results of tests on 1.0-in.-thick specimens for medium rate of shear on the low activity Upper Pepper material are shown in Table 5 and in Plate 22. Normal loads for these tests included loads up to 18.0 tsf. The envelope and stress circle shown in Plate 22 indicate a maximum past pressure of approximately 19.0 tsf, which approaches the value indicated from geologic history. From the geologic history discussed in

paragraph 13 and assuming that the 600-ft total displacement in the faults once represented the minimum overburden load on the Pepper formation, then a maximum past pressure of at least 20 tsf can be inferred. As shown in Plate 14, a maximum past pressure of 6.0 tsf may be determined from the consolidation test data on this material. The apparent contradiction has not been resolved.

Triaxial Compression Tests

43. Unconsolidated-undrained triaxial compression tests were conducted on specimens of the Upper Pepper shale. Both constant strain (Q_n) and stress control (Q_{ss}) tests were conducted. Test data are summarized in Table 6. The test specimens were trimmed from samples taken at approximately equal elevations since the bedding appeared to be essentially horizontal. The specimens were trimmed so that the normally horizontal plane was inclined at preselected angles of 45 and 60 deg. Water content and classification test specimens were taken from trimmings adjacent to the triaxial specimens. All specimens were 1.4 in. in diameter and 3.0 in. high. Two rubber membranes, separated by a thin layer of silicone grease, were placed over each specimen prior to assembly in the triaxial chamber. Tap water was used as the chamber fluid. The induced pore pressures were measured at the top of each specimen through a porcelain disc having a bubbling pressure of 30 psi; the tubing connecting the disc to the pore pressure measuring interface was 1/16-in. stainless steel with an inside diameter of 0.02 in. and a total length of about 30 in. Chamber pressures were 1.5, 3.0, 6.0, and 12.0 tsf. Pore water pressures were allowed to become stable, which required from 1 to 3 days, before axial loading was commenced. The Q_n tests were conducted at a rate of strain of 0.001 in./min, intended to effect failure in 15 to 20 min, except for one set of specimens which was tested at a more rapid rate. Pore pressure measurements were made during shear. The tests were discontinued after developing a strain of about 10 percent, and the total specimens were used for final water content determination. The Q_{ss} tests were loaded in axial stress increments of approximately 0.1 tsf, applied through a dead load system at minimum time intervals of 24 hr. Pore pressure measurements were made during shear. The rates of loading were believed to be sufficiently slow for equalization of pore pressure. Failure, when it occurred, was total, and no postfailure data could be

obtained. Water content determinations were made on each entire specimen.

44. Results of strength determinations were of such erratic nature that no analyses were possible, but the relationship of pore pressure to chamber pressure at various stages in the test, shown in Plate 23, presents some interesting data. The pore pressure values versus the chamber pressure prior to the application of deviator stress for the Q_n and Q_{ss} tests are shown in Figure 1 of Plate 23. In both cases a negative pore pressure of approximately 1.3 tsf (18 psi) at zero chamber pressure is indicated. The rate of increase of pore pressure with respect to increase in chamber pressure is shown to be approximately 0.88:1.00. The application of deviator stress induced additional pore water pressure until, at failure, the ratio of pore pressure to chamber pressure was slightly greater than 1.00:1.00 in the Q_n test and less than 1.00:1.00 on the Q_{ss} tests.

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

45. The limited number of tests conducted on materials having such a broad and complex distribution of properties as demonstrated by the subject materials will not produce final conclusions. However, this investigation reaffirmed that uniform visual and tactile characteristics of a clay shale mask a bewildering array of subvisual and subtactile, but extremely important properties. Rather than conclusions, the results will be treated as leading to inferences and suggestions.

Identification tests

46. Based on the results of the tests conducted on the subject materials, it can be inferred that the use of solutions in testing that contain ions which were present in the natural environment has no material effect on either the Atterberg limits or grain-size distribution tests. This is suggested by the results of limits tests conducted with natural ground water and the results of hydrometer tests with deflocculants containing ions which were also present in the ground water. The deflocculants and the natural ground water were both heavily charged with sodium; therefore, any affinity of the clay minerals for sodium would have been satisfied in their natural environment. The use of distilled or tap water probably would not change the characteristics of the clay minerals because no leaching process was performed; the material was simply given access to the "foreign" water.

47. Drying the materials prior to preparation of test specimens for Atterberg limits and grain-size analysis had a significant effect on the test results. The effect was to increase the value of the liquid limit and to increase the percent of colloids.

48. The activity index proved to be valuable in identifying differences in materials which otherwise appeared to have fairly uniform characteristics.

Consolidation tests

49. All consolidation tests showed some degree of disturbance. It is noteworthy that the tests conducted in the more precisely fitting test equipment showed a greater degree of disturbance than did the other tests which were conducted in test equipment which had not been repaired. The major difference in properties of these specimens is that they exhibited a very low

activity index. Apparently, the lower the activity index, the more susceptible the material is to disturbance. It should be noted that "disturbance" as used here does not necessarily mean a distortion or physical manipulation of the material which would result in visible disturbance but is used to mean a relaxation of diagenetic bonds or intergranular stresses which would probably be invisible to the eye and not physically obvious in the texture of the material. It is recognized that some small disturbance may have occurred to the entire sample in the field operation. This small disturbance, therefore, is reflected in all the test results.

50. Consolidation tests conducted on the noncemented Pepper shale showed preconsolidation pressures only a fraction of that which could be inferred from the geological history of the area. Although the tests were loaded to only 64 tsf, it would be difficult to conceive of a change in the slope of the e-log p curve which would result in higher indicated preconsolidation pressure than had the specimens been loaded to ten times this load. Consolidation tests conducted on the lightly cemented Del Rio shale indicated preconsolidation pressures somewhat higher than those on the Pepper shale.

Direct shear tests

51. Direct shear tests showed a significant decrease in shear strength with decrease in specimen thickness and a slight decrease in shear strength with the slower rate of strain. The tests indicated that both friction angle and cohesion were affected by specimen thickness, but only the cohesion component was affected by the rate of strain.

52. The direct shear test on the high activity Upper Pepper zone showed a higher shear strength than did comparable tests on the low activity Upper Pepper zone.

53. The maximum past pressure for the Pepper shale estimated from the direct shear tests is several times the amount which could be determined from the consolidation test results.

Triaxial compression tests

54. Based on analysis of triaxial compression test results, a significant change in the state of the material is suggested by the changes in pore water stresses from in situ to laboratory conditions.

Recommendations

55. Recommendations are as follows:

a. High temperatures should not be used in testing specimens containing the mineral montmorillonite. This would include tests related to moisture content, Atterberg limits, grain-size analysis, and apparent specific gravity. There are sufficient data in existing literature to support these recommendations, and the tests conducted for this investigation merely offer further support.

b. Additional tests should be conducted to investigate the apparent relation of activity index and sample disturbance in highly overconsolidated clays.

c. Investigations should be conducted to determine the expansion pressures exhibited by clay shales, especially those containing montmorillonite. This appears to be one of the more elusive properties of the materials and one which has a profound effect on consolidation and strength test results. The consolidation tests show successively larger expansion pressure for increasing thicker specimens. The triaxial compression tests indicate high suction pressures. These two inconsistencies have not been resolved.

d. Specimens no thinner than 1.0 in. should be used for direct shear tests on clay shales. The across edge failures demonstrated by many of the thinner specimens cast considerable doubt on the validity of these tests. It is recommended that other types of shear tests (torsional or plane strain) be conducted on similar material so that the size and shape of the failure plane can be related to the indicated unit shearing resistance.

e. The use of a nonpolar fluid should be investigated to make drill mud when drilling in potentially expansive soils. Also, the drill mud should be made by mixing natural material from the shale with a nonpolar fluid rather than a commercial product.

PART II: COMMENTS ON LABORATORY TESTING

CHAPTER 1: INTRODUCTION

56. Materials used for the investigation consisted of three clay shales from the Waco Dam area. The materials are identified as (a) Upper Pepper. (b) Lower Pepper, and (c) Del Rio shales. The materials are described geologically in the following paragraphs.

Pepper Shale

57. The Pepper is a soft, noncalcareous, thin- to medium-bedded, fossiliferous, fissile, black, compaction shale with occasional nodular claystone seams, siltstone seams, and sandy seams throughout. It slakes readily upon exposure. Although the Pepper shale is not geologically subdivided, test results show a distinct difference in the upper and lower portions of the materials.

Del Rio Shale

58. The Del Rio is a soft, calcareous, medium- to thick-bedded, fossiliferous, nonfissile, medium gray to greenish gray, clay shale with one thin bentonite seam near the top. It contains occasional marly, highly calcareous zones and argillaceous limestone seams; occasional thin, disclike poorly developed clay-ironstone concretions near the base; and occasional thin, softer, dark gray to clay shale seams throughout.

59. The testing consisted of classification, consolidation, direct triaxial compression shear, and triaxial compression tests. All specimens for consolidation, direct shear, and triaxial compression testing were trimmed in the laboratory moist room, which is kept at high humidity by constantly operating spray nozzles and an air-conditioning unit. During work on the clay shale materials, the room was kept closed off from the rest of the laboratory, and no samples were opened nor specimens prepared when the measured relative humidity was below 90 percent. Trimming tools were those ordinarily used for soils materials, such as, knives of various kinds and straightedges. Specimens were trimmed directly into the test containers and were never pushed from a cutting ring into the testing device. All moisture contents were obtained

from specimens dried at approximately 105° C temperatures in a forced-draft type oven.

60. Mineralogical composition of the three materials was as follows:

	Composition, Percent by Weight		
	Upper Pepper	Lower Pepper	Del Rio
Montmorillonite	30-50	25-30	15
Illite	3-10	10-25	20
Kaolinite	20-25	25-30	15
Calcite	0	0	20
Quartz	15	10-15	20

CHAPTER 2: IDENTIFICATION TESTS

Phase 1

61. Grain-size analysis specimens were oven-dried and 50-g portions were slaked for a minimum period of 24 hr. None of the materials slaked completely, and dispersion was accomplished with a blender. The specimens were worked into standard hydrometer jars. Ten millilitres of a stock solution (41 g/ℓ) of Calgon were added to prevent flocculation. Hydrometer readings were taken 1, 5, 30, and 120 min, and 24 hr after shaking and setting. Test results are shown in Plates A1 through A6.*

62. Atterberg limits specimens were covered with distilled water for at least 24 hr, processed in the blender, and washed through a No. 40 screen. Excess water was removed by the use of plaster of paris bowls. Liquid limits were obtained by the simplified (one-point) method. Plate A6 shows the relationship between the liquid limits and plasticity indices. Three tests were conducted on material after oven-drying; it is noted that the Upper Pepper specimen showed an increased value for liquid limit after drying, with the plastic limit remaining unchanged. The effect of drying upon the Atterberg limits of montmorillonite clays has been described by Lambe (1951) as unpredictable.

Phase 2

63. Additional identification tests were conducted on the Upper Pepper shale. The results shown in Plates A7 through A14 were obtained on material which had been oven-dried prior to testing with the curves adjusted to show no more than 100 percent of any size particles. The deflocculant used in these tests was "Calgon," a buffered sodium hexametaphosphate with other phosphates in various amounts. Plate A14 shows the effect of oven-drying on grain size. The reduction of grain size is thought to be the effect of reducing the basal spacing of the montmorillonite particles upon drying. Also shown in Plate A14 is the effect of different manual-recommended deflocculants. There was no

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* Plates referred to in Part II have been microfilmed and are included in Appendix A.

notable difference in test values when using either Calgon, sodium tripolyphosphate, or sodium hexametaphosphate.

64. Additional Atterberg limits tests were conducted, using distilled water and natural ground water in preparing the samples. As before, the specimens were not oven-dried prior to testing. The liquid limit values obtained using the ground water as the preparation fluid showed values ranging from 0 to 5 percent greater than the values obtained by using distilled water as the preparation fluid.

65. The ground water was obtained from wells drilled into the Pepper shale formation. A comparison of the chemical analyses of the ground water with Dallas tap water is shown below.

Water Analysis Test	Ground-water Results, ppm	Tap-water Results, ppm
Total solids	1275	170
Dissolved solids	1275	170
Calcium, as Ca	0.1	23
Magnesium, as Mg	2.7	4.6
Sodium and Potassium, as Na	553	27
Sulfates, as SO_4	0.0	44
Chlorides, as Cl	54	30
Carbonates, as CO_3	108	14
Bicarbonates, as HCO_3	1115	10
Nitrates, as NO_3	0.3	4.0
Alkalinity (phenolphthelein), as $CaCO_3$	90	12
(methyl-orange), as $CaCO_3$	1094	32
Iron, as Fe (total)	0.04	0.01
Iron, as Fe (dissolved)	0.01	0.01
Silica, as SiO_2	14	6.2
Fluoride, as F	9.5	0.60
Manganese, as Mn (total)	0.00	0.00
Manganese, as Mn	0.00	0.00
Total hardness, as $CaCO_3$	16	76
Carbonate hardness, as $CaCO_3$	16	32
Noncarbonate hardness, as $CaCO_3$	0	44
Free carbon dioxide, as CO_2	16	0.00

(Continued)

Water Analysis Test	Ground-water Results, ppm	Tap-water Results, ppm
Resistivity, ohm/cm^3, at 25° C	660	3486
Dissolved solids, as NaCl (by conductance)	700	137
pH value	8.2	9.6
Specific gravity at 60° F (by pycnometer)	1.001	1.000
(by hydrometer)	0.999	0.997

Computations of a hypothetical nature indicate that the chief mineral compound present in the ground water is sodium carbonate or bicarbonate; in tap water calcium carbonate, sodium chloride, and sodium or calcium sulphate are present in nearly equal amounts.

CHAPTER 3: CONSOLIDATION TESTS

Phase 1

Procedure

66. Controlled-expansion consolidation tests were conducted on specimens of 1/4, 3/8, 1/2, and 1 in. nominal thickness. The actual initial thickness of each specimen was determined by 0.001-in. dial gage measurements at four points near the circumference and at a center point. The thickness of a given specimen did not vary more than plus or minus 0.001 in. from point to point. Wetted filter papers were placed over each face of a specimen and the consolidometer assembly completed, with saturated porous stones above and below the specimen.

67. The consolidometer was placed in the loading device. A 0.2-tsf pressure was applied and the specimen inundated with de-aired distilled water. Expansion was controlled by the addition of pressure in increments of 0.25 tsf. The total pressure required to contain expansion is shown on the applicable Consolidation Test Report sheets.

68. The loading schedule was 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, 64.0, 16.0, 4.0, and 0.1 tsf, with loading beginning at the pressure next above the expansion pressure. The Upper Pepper (Plates A15 through A27) and the Del Rio (Plates A48 through A62) specimens were loaded at 24-hr intervals, except on weekends. Not all of the latter, however, completed rebound under reduced pressure in 24 hr, and rebound loads remained unchanged for periods up to 7 days. The third clay shale, the Lower Pepper (Plates A28 through A47) did not reach equilibrium in 24 hr under any of the applied pressure increments, and the rate of load application was determined by the shapes of the time-consolidation curves. The time interval between load increments was from 3 to 6 days.

69. Southwestern Division laboratory loading devices are not designed to permit rebound at zero load, and the final rebound occurred under pressure of 0.1 tsf. When time curves indicated completion of rebound, the water jacket was drained, the 0.1-tsf pressure was removed, and the consolidometer was disassembled. Free water was carefully blotted from the specimen ring. Material which had extruded around the edge of the upper porous stone was removed and placed in a moisture tin. The thickness of the specimen was then measured, as

described above. The specimen was pressed from the ring and surface material scraped away and placed in a moisture tin for oven-drying. The remainder of the specimen was placed in another tin. The water content determined from the latter was later used as the "final" water content.

Computations

70. Void ratios corresponding to the various pressures were computed from the dial readings. These values are plotted on the Consolidation Test Report forms. It is noted that two curves appear on most of the void ratio-log pressure plots, one a solid line and the other line broken. These curves represent the void ratios attained by a specimen 24 hr after load application and at the end of the total time under that pressure. Curves for the Del Rio and Upper Pepper tests indicate no appreciable differences in the 24-hr total curves except in the rebound lag of the Upper Pepper 1-in. test, where side friction is believed to have been large. The Lower Pepper, however, presents a different picture, particularly for the 1-in. specimen, where substantial amounts of consolidation and rebound occurred after the first 24 hr.

71. Following the consolidation test data are Plates A63 through A68, which show the variation in unit deformation with specimen thickness. One of each pair of plates corresponds to the 24-hr e-log p curves; the second plates correspond to the total time e-log p curves. Unit compression is shown to increase greatly with decrease in initial specimen thickness, as shown in Plates A69 through A71.

Analysis

72. The variations in unit deformation were considered to have several possible causes, among them the error resulting from the extraction of material from the ring, disturbance of specimens caused by trimming, or some form of structural breakdown.

73. Initial study did not support extrusion as the total explanation because the quantities of extruded material bore no constant relation to specimen thickness, as indicated by the following tabulation.

Material	Nominal Initial Thickness, in.	Extruded Material Total Grams	Extruded Material Grams/Inch of Thickness
Upper Pepper	1/4	1.4	6.1
	3/4	2.4	5.7
	1/2	3.7	7.5
	1	3.1	3.1

(Continued)

Material	Nominal Initial Thickness, in.	Extruded Material Total Grams	Extruded Material Grams/Inch of Thickness
Lower Pepper	1/4	3.9	17.1
	3/8	4.7	12.8
	1/2	5.4	10.9
	1	22.7	22.7
Del Rio	1/4	1.6	7.2
	3/8	1.4	3.7
	1/2	--	--
	1	3.3	3.3

74. An effort was made to evaluate trimming disturbance, using the methods of Van Zelst (1948). The shapes of the e-log p curves did not indicate that this could be accomplished, but a number of trials were made. No reasonable assumptions could be made, however, which would result in credible results.

75. A test devised to evaluate the possibility of structural failure under load was not successful. A cylindrical specimen having a diameter of about 2.5 in. and a height of 1.5 in. was placed in a metal chamber similar to a triaxial chamber, but with provisions for measuring internal pore pressure and volume change. Chamber pressures exceeding 30 tsf were applied, with very considerable pore pressure lags, despite the likelihood of the specimen having been nearly saturated. The maximum pore pressure measured was equal to about one-half the chamber pressure; as time continued, however, pore pressure fell off consistently to a value of about one third of the chamber pressure. The occurrences described occurred over a period of several months. Volume change measurements indicated a constant though slight decrease in specimen volume.

76. Plates A69 through A71 show the relationship between specimen thickness and deformation in another manner. If specimen thickness had no effect on unit compression, the curves of these three plates would be horizontal lines. If the e-log p curves of Upper Pepper shale are re-examined, it will be noted that they are typically shaped up to a point: each curve is initially more or less horizontal, then bends downward into its virgin compression curve. However, the 3/4- and 1/2-in. curves bend more steeply downward after the 32-tsf increment, and the 1/4-in. curve bends after the 16-tsf increment. If these sudden increases in deformation are attributed to extrusion and the earlier straight-line portion of each curve is extended to 64 tsf, deformation versus specimen thickness curves for the Upper Pepper become as shown by the

dashed lines. The remaining curvature in all the curves is attributable to minor amounts of extrusion or to specimen disturbance.

77. Additional weight is given the extrusion hypothesis by final saturation computations. Using thickness changes as measured by test dials, S_f values range as high as 130 percent. When, however, final saturations were computed using the directly measured final thicknesses, values ranging from 91 to 107 percent as reported on the individual Test Report forms were obtained. An effort was made early in the study to correct final volumes by the amount of extruded material; since reasonable S_f values were not obtained, it must be assumed that only a portion of the extruded material was recovered.

Phase 2

78. Additional consolidation tests were conducted on samples of Upper Pepper shale during Phase 2. Four series of tests were conducted as follows:

- a. Series 1: 1/4-, 3/8-, and 1/2-in. thick specimens; inundation fluid was ground water.
- b. Series 2: 1/4-, 3/8-, and 1/2-in. thick specimens; inundation fluid was de-aired distilled water.
- c. Series 3: 1/4- and 1-in. specimens; 1/4-in. loads changed daily; 1-in. loads changed every 13 to 14 days.
- d. Series 4: 1-in. specimens; Teflon-lined ring and greased ring.

79. Results of consolidation tests are presented graphically in Plates A72 through A142.

- a. Series 1: Plates A72 through A79 show standard time plots. No corrections have been made for apparatus deformations. The same data are presented in Plates A96 through A106 with certain adjustments to permit direct comparison of unit deformation with thickness. First, it was assumed that all the deformation occurring in the first 0.1 min after loading is apparatus deformation. Also, the time scale for the various thickness is compacted from the theoretical relationship $t_2/t_1 = (H_2)^2/(H_1)^2$.

  In Plate A137 are shown pressure-deformation curves. The left-hand plot is a standard plot, based on the adjusted time curves shown in Plates A96 through A136. The plots shown on the right-hand side of the plate are curves based on primary consolidation only.
- b. Series 2: Plates A80 through A87 show the standard time plots. These data are presented in Plates A108 through A119 with the adjustments noted above. The pressure-deformation curves are shown in Plate A138; the right-hand set of curves are based on primary consolidation alone.

c. Series 3: Plates A88 through A91 show the standard time plots. These data are presented in Plates A120 through A130 with the adjustments noted above. The pressure-deformation curves are shown in Plate A139; the right-hand set of curves is based on primary consolidation alone.

d. Series 4: Plates A92 through A95 show the standard time plots. These data are presented in Plates A131 through A136 with the adjustments noted above. The pressure-deformation curves are shown in Plate A140; the right-hand set of curves is based on primary consolidation alone.

80. Plates A137 and A138 indicate the major cause of the offset pressure deformation curves (left-hand plots) to be the result of the larger effect of secondary compression in the 1/4-in. specimens, etc. Series 3 tests were conducted to check this. Actual initial specimen thicknesses of the Series 3 specimens were 0.275 and 1.000 in.; the ratio of times required for equivalent U values is theoretically $(1.000)^2/(0.275)^2 = 13.2$. The thinner specimen was therefore loaded daily and the thicker specimen every 13 or 14 days. Series 4 tests were conducted for the purpose of checking side friction effects. The grease used contained molybdenum disulfide (Bansbo 1960). In plotting the primary-only pressure-deformation curves, it was assumed that, in cases where the time plot did not fit the theoretical pattern (i.e., secondary compression masked out the primary, as in Plate A36), primary was so small as to be insignificant, and was called zero.

81. Omitting Series 3 tests, which do not match the other tests in several respects, the following observations are made:

a. C_α has a maximum value of 0.0015 to 0.0018 at pressures to 2.0 tsf and an average value near 0.0025 at pressures of 4.0 tsf and above, indicating the maximum past pressure is between 2.0 and 4.0 tsf.

b. Values of t_{50} for the 1/4-, 3/8-, and 1/2-in. specimens of Series 1 and 2 are similar.

c. Values of t_{50} for 1-in. specimens of Series 1, 2, and 4 are in good agreement.

d. Values of t_{50} for 1-in. specimens are consistently lower than for the 1/4-, 3/8-, and 1/2-in. specimens, with the difference increasing with pressure to 8.0 and 16.0 tsf, then decreasing again:

Pressure tsf	t_{50}, min Average 1/4, 3/8, 1/2 in.	Average 1 in.
1.0	9	--
2.0	8	6
4.0	20	16
8.0	28	15
16.0	20	9
32.0	14	9
64.0	12	9

82. The offset between pressure-deformation curves still apparent after adjustment for secondary compression is a result of the difference in expansion pressure. Expansion pressures appear to vary with thickness as shown below:

Series	Expansion Pressure, tsf 1/4 in.	3/8 in.	1/2 in.	1 in.
1	0.25	0.5	0.75	1.0
2	0.25	0.5	0.75	1.25
3	0.75			1.0
4				0.75 (Teflon)
4				1.0 (Greased)

Plate A139 illustrates this point. The 1.0-tsf pressure increment gave a time curve in the 1/4-in. test permitting definition of primary consolidation of about 0.012 in. The same load on the 1-in. specimen, however, resulted only in secondary, and primary consolidation was zero. The two curves remain separated by about this distance over their full lengths. It may be that application of the methods of Hansen (1961), Wahls (1962), or Crawford (1964) may permit some less restrictive assumption as to what constitutes primary and secondary compression, but all of these methods have not yet been investigated. The differences in expansion pressure defy explanation but could reflect apparatus inadequacies.

83. Plate A141 shows, for convenience and as a matter of interest, the magnitude of primary compression corresponding to individual loads. Plate A142 is a summation of pressure-deformation (primary only) curves for all of the 1-in. thick specimens. Only the Series 3 test is appreciably different. There is no readily available explanation for the results of Series 3 tests, which have C_α values as high as 0.0051 and t_{50} values to 50 min. Apparently the material itself is different, but the difference is unknown.

84. The initial moisture contents for all specimens averaged

21.3 percent with a range of plus or minus 0.2 percent. The initial dry density averaged 108 pcf with an average of 0.5 pcf and initial saturation averaged 100 percent with a range of plus or minus 2 percent. Final saturation values were near 100 percent for the thicker specimens and as high as 108 to 109 percent for the 1/4-in. specimens. For all S_f values to be 100, all pressure-deformation curves should match the curve for the 1-in. specimens.

CHAPTER 4: DIRECT SHEAR TESTS

Program

85. Twelve sets of 3- by 3-in. specimens were trimmed from each of the materials. A set consisted of three specimens to be sheared under normal stresses of 1.5, 3.0, and 6.0 tsf. Thicknesses and times to failure for the twelve sets are tabulated below.

Net	Specimen Thickness, in.	Desired Time to Failure
1	1/4 (nominal)	6 min
2		6 hr
3		6 days
4	3/8 (nominal)	6 min
5		6 hr
6		6 days
7	1/2 (nominal)	6 min
8		6 hr
9		6 days
10	1 (nominal)	6 min
11		6 hr
12		6 days

Actual specimen thicknesses did not vary from the desired thicknesses by more than 0.004 in., except for the 1-in. specimens, which measured from 1.000 to 1.020 in. Because the rate of shear required to effect failure in the listed times could not be accurately estimated, the tests corresponding to 6-min, 6-hr, and 6-day failure are hereinafter referred to as fast, medium, and slow tests. In some cases more than one test was conducted.

Procedures

86. Test specimens were trimmed into "cutters" which are split horizontally at the midplane. The cutter with the specimen is placed directly into the shear box. The plane along which shear stress is applied coincides with the plane between halves of the cutter. These features are shown on the shear box diagram. The specimens were then inundated with tap water and permitted to consolidate under 1.5-tsf normal pressure for at least 16 hr, after which the normal pressures on two of the three specimens of a set were increased to 3.0 and 6.0 tsf.

87. After 24 hr of consolidation under the full load, the upper half of the shear box, hereafter referred to as the yoke, was raised to a position about 0.05 in. above the lower half of the box. The yoke was clasped to the piston by means of machine screws. The two halves of the cutter remained in contact along lips having about 0.1-in. width.

88. Shear was begun, with the following nominal rates having been selected:

Fast tests	0.006 in./min
Medium tests	0.00008 in./min
Slow tests	0.000004 in./min

The rates actually achieved varied somewhat from the above, and are shown on the individual Test Report forms. The rates reported on these plates are averaged values from:

$$\text{Rate} = \frac{\text{(Final horizontal dial reading) - (initial horizontal dial reading)}}{\text{Total elapsed time to failure}}$$

The rate of shear was closely controlled during the working day by manual adjustment of variable speed reducers ("Zero-Max") but tended to drift during the night and over weekends, resulting in deviations of considerable magnitude in some instances.

89. A test was discontinued when failure had occurred. Failure was considered to have occurred either when a continuing drop in shear resistance was noted or when the shear resistance remained at a constant level for a long period of time. Water contents were taken from the centers of specimens after test.

Test Results

90. Test data are shown on Direct Shear Test Report forms (Plates A143 through A181). Several factors prevented the preparation of all of the specimens of a given set at the same time and, in some cases, it was necessary to use portions of several samples to complete a set. The samples used and their depths are shown across the bottoms of the Test Report forms.

91. Failure sketches are shown in the upper right-hand blocks of the Direct Shear Test Report forms. The mode of failure in the thinner specimens

was difficult to distinguish in most instances. Where failure across edges was indicated, the adjacent material was usually soft and mushy and the fractures ill-defined. The same condition or mushiness existed around the entire periphery of many of the specimens. It is also noted that the pictured displacement between upper and lower halves of the specimens is not a scale representation; in some instances the apparent movement was extremely small, resulting from compression rather than shear. A point of interest is the tendency of the 1-in. specimens to fail along horizontal planes, as against the across-corner failures of the thinner specimens. Close examination of the 1/2-, 3/8-, and 1/4-in. specimens showed a trend toward more steeply inclined fractures as thickness decreased, but the mushiness of the failure zones made it impossible to obtain measurements sufficiently accurate to verify this completely.

Discussion

92. While the investigation herein reported was intended chiefly to investigate the effects of varying specimen thickness and varying rate of shear, other variables might be expected to affect strength properties. Among these variables are density, water content, and plasticity.

93. Density and water content were found to vary as follows:

	Upper Pepper	Lower Pepper	Del Rio
Number of specimens tested	45	43	41
Average initial dry density, pcf	109	100	112
Number of specimens not within 2 pcf of average	5	15	18
Average initial water content, percent	20	26	18
Number of specimens not within 1 percent of average	3	18	10

The density and water content of the Upper Pepper specimens are relatively consistent from sample to sample.

94. Plasticity characteristics are shown in the following tabulation of liquid limits:

	Upper Pepper	Lower Pepper	Del Rio
Number of tests	5	7	6
Range of values	72-82	54-103	56-74
Average value	76	83	68
Number of tests not within 5 percent of average	1	5	4

The Upper Pepper is again shown to be the more uniform material.

CHAPTER 5: SHEAR STRENGTH SUMMARY

Phase 1

95. In Plates A182 through A184 are plots summarizing all the strengths obtained in each test series with the shear strength scale doubled to spread the points. Comparison of individual test strengths suggests that shear strength depends on both specimen thickness and rate of shear. Straight-line envelopes, if plotted between all similar points, are found to be predominantly convex upward and to the left in shape. If it is assumed that strength increases with normal stress as in ordinary soils, several points not meeting this requirement may be disregarded and the number of possible envelopes reduced. When this is done, a trend toward parallelness of envelopes is distinguishable. Envelopes which demonstrate this feature particularly well are shown with solid lines for the Upper Pepper and Del Rio shales. The dashed lines for Lower Pepper are discussed in a later paragraph.

96. In Plates A185 through A193 are plots showing the relationship between shear strength and time to failure. As might be expected from examination of the other data, the curves are erratic and do not lend themselves to other than arbitrary interpretation. The figures adjacent to symbols are liquid limits, and indicate that no statement of relationship between strength and liquid limit is justified by the data. The only one of the three materials in which a wide range of plasticity exists is the Lower Pepper, and a question exists as to whether liquid limit specimens were representative of the materials at the specific elevations at which the various direct shear specimens were taken.

97. Because of the high degree of parallelism exhibited by some of the straight-line envelopes shown on the summary plates, a working assumption was made that all the envelopes for a given material should be more or less parallel regardless of specimen thickness, rate of shear, or mode of failure. Frictional components of strengths are thus assumed to vary only slightly. Because of the uniformity of the Upper Pepper shale, these tests were selected for analysis according to this hypothesis. As noted earlier, the solid lines shown in Plate A194 are drawn between actual test points. The dashed lines are interpolated through at least one actual test point. The resulting family

of curves indicates generally parallel envelopes with slopes slightly increasing with specimen thickness.

98. Application of the interpolated values for the Upper Pepper shale to a shear strength versus log time plot is shown in Plate A194. Shear strength is shown to be a straight-line function of the logarithm of time to failure, over the range of times and pressures used. The single departure from this rule occurs in the curves representing the 1-in.-thick specimens. These curves bend downward between the symbols representing the medium and slow tests, shown respectively by open triangles and squares. The strengths used for the slow tests were defined by a dashed envelope, but if the interpolated envelope had been drawn through the unused test point at 1.5-tsf normal and 2.02-tsf shear stress, the resulting strength-time relationships would be represented by the dashed lines.

99. The spacing of the curves on this plate might be expected to follow some mathematical formula, and visual examination suggests that the spacing may be logarithmic. Accordingly, Plate A195 shows strengths at 10 min and 1,000 min plotted against the logarithm of specimen thickness.

100. The data for the Lower Pepper and Del Rio shales do not lend themselves to similar analyses because of the lack of uniformity between test specimens. Because this report is intended to present and discuss only the results of the tests conducted specifically under ES-529, the results of earlier tests of similar materials have not been considered, and a detailed study of the effects of such variables as plasticity, water content, and density has not been undertaken.

Phase 2

101. The direct shear tests conducted for Phase 2 of this investigation were conducted in much the same way as those in Phase 1. The major difference was in the use of natural ground water for the inundating fluid; whereas, in Plate 1 tests, tap water was used. In Phase 2 some of the specimens were subjected to normal loads of 12.0 and 18.0 tsf. The initial moisture content of the test specimens averaged 21.5 percent with a range of plus or minus 0.3 percent, densities averaged 106.9 pcf with a range of 1.0 pcf, and the initial saturation averaged 98 percent with a range of 2.0 percent.

102. Plate A202 shows results from Tests 1 through 9 at 1.5, 3.0, and

6.0 tsf normal pressures. The rate of shear was 0.0001 to 0.0002 in./min, thickness was 1 in., and the failure planes were horizontal. Shear stress was applied at the end of the specimen. The U. S. Army Engineer Waterways Experiment Station's view is that this invalidates the test results because the shear stress should properly be transmitted across the whole area through the porous stones. In the same way, strengths of the thin specimens, which failed across the corners, may lack significance because of slipping between specimen surfaces and porous stones, resulting again in stress concentration at the ends of the specimens. The different strengths for the different thicknesses may thus be functions of the length of failure path across corners.

103. Plate A203 presents results from tests 10 through 14 at 12.0 and 18.0 tsf normal pressures. For tests 10 and 11, at 18 tsf, the rate of shear was 0.001 to 0.002 in./min. For tests 12 and 13, at 18 tsf, and test 14, at 12 tsf, the rate of shear was 0.000004 in./min. Thickness was 1 in. and the failure planes were horizontal. The same remarks as in paragraph 102 also apply.

104. Plate A204 presents shear strength envelopes for all 14 tests. Envelopes of tests 1 through 9 were below original envelopes, depicting a similar strength angle. Envelopes through an average of 18.0-tsf strength and the origin are parallel to other envelopes.

105. It is of note that a single, smooth, curved envelope can be drawn through all the points up to normal pressure of approximately 14 tsf. This would suggest that all these points lie below the prestress effective pressure (U. S. Army Engineer Waterways Experiment Station 1961) or, in effect, the effective maximum past pressure is equal to or slightly greater than 14 tsf. This value approaches the magnitude of the load which is thought to have been applied to the Pepper shale in geologic history, but is strongly contradictory to the values obtained from consolidation testing. The values, derived from consolidation tests, were obtained from tests loaded up to 64.0 tsf and ranged from 2 to 5 tsf.

CHAPTER 6: DIRECT SHEAR TESTING EQUIPMENT

106. Early in the testing program it was decided to mount additional dials above the yoke to check tilting of the box during shear. The dial management is shown in Plate A196. Two extra 0.0001-in. dials were mounted and movement recorded during about one-fourth of the tests. Computations of vertical movement of the front and rear edges of the pistons were made using the formulas shown on the plate. Plates A197 through A199 show the computed movement at the front, middle, and center of the piston for three typical tests of 3/8-in. specimens. Plate A200 presents similar data for a 1-in.-thick specimen. The four plots are discussed separately as follows.

107. Plate A197 shows the tipping of the piston during Test 3 (Plate A146). The front edge of the piston is indicated to have moved downward initially while the rear edge moved upward. At the horizontal deformation approximately corresponding to failure, movement at both edges had virtually ceased, but resumed upon failure. The dial located at the center of the piston indicated a net downward movement; the computed movement at the center, however, was upward.

108. Plate A198 shows the tipping of the piston during Test 1 (Plate A160). The initial movement at the front edge of the piston was apparently downward and, at the rear, upward. Near failure, the curves reversed direction and, at the end of the test, the front edge had seemingly risen considerable distance, while the rear edge had returned to its initial elevation. The measured upward movement at the center of the piston was less than that actually measured.

109. Plate A199 shows the tipping of the piston during Test 3 (Plate A148). Movement at the front edge was upward; at the rear edge, movement was downward. Both actual and computed movements at the center of the piston were downward, with the actual movement greater than the computed.

110. Plate A200 shows the tipping of the yoke during Test 1 (Plate A152). All tests of 1-in.-thick specimens were conducted slightly differently from those of the thinner specimens. The design of the Southwestern Division direct shear boxes is such that the yoke cannot be secured to the piston by the end screws when the specimen thickness exceeds about 0.75 in. The yoke was therefore suspended from the piston by three hangers bearing on the surface of the piston, and the movement of the yoke was thus semi-independent of the piston.

The curves plotted on Plate A200 represent the movement of the yoke at points corresponding to the front and rear edges of the piston. Both front and rear moved upward during the test. The upper curve, representing the front of the yoke, rose sharply at the beginning, flattened out at a point corresponding to failure, then began an up-and-down cycling in which the crests and troughs were approximately repeated. The lower curve showed the same cyclic movement, but is offset about one-fourth of a cycle and had a much decreased magnitude. The movement at the rear is undoubtedly restricted by friction at the contact between the rear of the piston and the yoke.

111. The shapes of the curves of the above plates are dependent upon the mode of failure, and the pivot point concept utilized in obtaining values for Δ_f and Δ_r (change in height at front and rear edges of piston, respectively) is not totally valid, particularly after failure. Nonetheless, the curves demonstrate that tipping of the yoke and piston occur before as well as after failure.

112. The tipping of the yoke is caused by the action of two systems of couples which exist in the devices. These are shown in Plate A201. These couples have little effect in the usual direct shear test, because the force is relatively small and because couple 1 is relieved in some degree by plastic deformation of the specimen. In a brittle, high-strength material, however, both couples can be of considerable magnitude. Plate A200 may be used to demonstrate that the action of each couple brings about an answering action from the other, so that a self-perpetuating system of ups and downs exists. Two possibilities are raised by the recognition of yoke tipping: (a) the variation in normal stress distribution may affect failure, and (b) the edges of the specimens may be broken off by the rotational movement of the yoke.

CHAPTER 7: TRIAXIAL COMPRESSION TESTS

113. Unconsolidated-undrained triaxial compression tests (Plates A205 through A236) were conducted during the program's second phase. Both quick shear and slow shear tests were conducted. The quick shear is identified as Q_n , the slow as Q_{ss} . Test procedures were further modified so that the normally horizontal plane was inclined at 60 and 45 deg from the horizontal. The specimens were placed in the triaxial chamber and the indicated chamber pressure was applied. Induced pore water pressure was allowed to stabilize before the shear test. The Q_n tests were conducted by strain control at the rate of 0.001 in./min. The Q_{ss} tests were conducted by stress control, at the rate of 0.1 tsf/day or less.

114. Results of tests are summarized as follows:

Q_n	(60 deg)	2.4± tsf
Q_n	(45 deg)	1.8± tsf
Q_n	(45 deg)	1.0± tsf (along visible joint) 1.8± tsf (secondary failure)
Q_{ss}	(60 deg)	1.8± tsf
Q_{ss}	(45 deg)	1.0± tsf

It is noted that the Q_n tests exhibit greater strength than the Q_{ss} tests and the Q_n tests exhibit a much more brittle type stress-strain curve. Physical properties of the test specimens are shown below:

Initial water contents, all tests	= 21.0 ± 0.31 percent
Initial dry densities, all tests, except Q_n (45 deg with visible joint)	= 108.2 ± 0.7 pcf
Initial dry densities, Q_n (45 deg with visible joint)	= 107.2 ± 0.1 pcf
Initial saturation, all tests but Q_n (45 deg with visible joint)	= 99 - 101 percent
Initial saturation, Q_n (45 deg with visible joint)	= 97 percent

115. At the end of the earlier Q_{ss} tests, the chamber water smelled strongly of hydrogen sulfide and the membrane and inside of the chamber were stained black. A test gave a pH value of 6.4 against the initial 9.6. A very small amount of disinfectant was added to the chamber water on following tests, resulting in the clearing up of this problem.

BIBLIOGRAPHY

Bansbo. 1960. "Consolidation of Clay, with Special Reference to Influence of Vertical Sand Drains," Proceedings No. 18, Swedish Geotechnical Institute.

Bjerrum, L. 1967. "Progressive Failure in Slopes of Overconsolidated Plastic Clay and Clay Shales," Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 93, No. SM5.

Casagrande, A., and Hirschfeld, R. C. 1960. First Progress Report on Investigation of Stress-Deformation and Strength Characteristics of Compacted Clays, Soil Mechanics Series No. 74, Harvard University, Cambridge, Mass.

Casagrande, A., and Poulos, S. J. 1964. Fourth Progress Report on Investigation of Stress-Deformation and Strength Characteristics of Compacted Clays, Soil Mechanics Series No. 74, Harvard University, Cambridge, Mass.

Crawford, C. B. 1964. "Interpretation of the Consolidation Test," Journal of Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 90, No. SM5, Proceedings Paper 4056.

Grim, R. E. 1953. Clay Mineralogy, McGraw-Hill, New York.

Hansen, B. 1961. "A Model Law for Simultaneous Primary and Secondary Consolidation," Proceedings of 5th International Conference on Soil Mechanics and Foundation Engineering, Vol 1, Paris.

Hvorslov, M. J. 1960. "Physical Components of the Shear Strength of Saturated Clays," Research Conference on Shear Strength of Cohesive Soils, Boulder, Colo.

Lambe, T. W. 1951. Soil Testing for Engineers, John Wiley & Sons, New York.

Means, R. E., and Parcher, J. V. 1963. Physical Properties of Soils, Charles E. Merrill Books, Columbus, Ohio.

Schmertmann, J. H. 1955. "The Undisturbed Consolidation Behavior of Clay," Transactions, American Society of Civil Engineers, Vol 120, Paper No. 2775.

Seed, H. B., Woodward, R. J., and Lundgren, R. 1962. "Prediction of Swelling Potential for Compacted Clays," Journal of Soil Mechanics and Foundations Division, Vol 88, No. SM3.

__________. 1964. "Clay Mineralogical Aspects of the Atterberg Limits," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 90, No. SM4.

Skempton, A. W. 1953. "The Colloidal 'Activity' of Clays," Proceedings of the 3rd International Conference of Soil Mechanics and Foundation Engineering, Vol 1, Switzerland.

Underwood, L. B. 1967. "Classification and Identification of Shales," Journal of the Soil Mechanics and Foundation Division, American Society of Civil Engineers, Vol 93, No. SM6.

U. S. Army Corps of Engineers. 1965. "Laboratory Soils Testing," Engineer Manual EM 1110-2-1906, Washington, D. C.

U. S. Army Engineer District, Fort Worth. 1963. "Shear and Consolidation Tests on Foundation Material," Report on Embankment Slide and Reanalysis of Design (Waco Dam), Vol IV, Fort Worth, Tex.

U. S. Army Engineer Waterways Experiment Station. 1961. "Physical Components of the Shear Strength of Saturated Clays," Miscellaneous Paper 3-428, Vicksburg, Miss.

Van Zelst, T. W. 1948. "An Investigation of the Factors Affecting Laboratory Consolidation of Clays," Proceedings of 2nd International Conference on Soils Mechanics and Foundation Engineering, Vol III, Rotterdam.

Wahls, H. E. 1962. "Analysis of Primary and Secondary Consolidation," Journal of the Soil Mechanics and Foundations Division, American Society of Civil Engineers, Vol 88, No. SM6, Proceedings Paper 3373.

Table 1

Identification Tests

Boring No.	Depth, ft	Natural Moisture Content: No. Tests	Range	Average	Soil Indices Tested with Distilled Water: LL	PI	Net Ground Water: LL	PI	Grain Size Analyses* Percent Finer than: 0.074 mm	0.010 mm	0.002 mm	Activity Index PI/(% 0.002 mm - 10)
					Upper Pepper Shale							
8A6C-445	50.0-50.9	7	19.0-20.5	19.9	78	53	--	--	81	57	28	2.94
	50.9-51.8	8	16.7-20.6	19.1	82	59	--	--	--	--	--	--
	51.8-52.7	6	19.0-20.0	19.5	74	53	--	--	82	61	31	2.52
	52.7-53.3	4	19.7-20.5	20.1	--(86)**	--(63)**	--	--	--	--	--	--
	53.5-54.5	10	20.0-2Q.7	20.4	72	50	--	--	87	61	30	2.50
	54.5-55.4	9	19.0-20.0	20.0	73	49	--	--	83	61	28	2.72
	55.4-56.2	6	19.7-20.6	20.1	--	--	--	--	--	--	--	--
8A6C-446	25.5-26.2	2	21.2-21.7	21.5	68	47	--	--	--	82	40	1.57
	26.8-27.8	-	-	--	--	--	--	--	--	--	--	--
	27.8-28.7	4	21.2-21.4	21.3	67	44	70	48	--	90	51	1.42
	28.7-29.6	1	-	24.8	--	--	70	47	--	--	--	--
	29.6-30.2	1	-	23.4	65	43	68	46	--	87	47	1.19
	30.2-31.0	2	20.9-21.0	21.0	64	41	67	45	--	86	41	1.32
	31.0-31.5	4	21.1-21.4	21.3	64	41	68	46	--	88	48	1.08
	31.5-32.4	1	-	25.8	65	43	66	44	--	93	54	0.98
	32.4-33.4	6	21.1-21.6	21.3	69	46	71	48	--	92	53	1.07
	33.4-34.0	1	-	23.0	71	48	71	50	--	91	51	1.17
8A6C-447	28.3-29.2	4	21.0-21.1	21.0	65	43	66	44	--	85	50	1.07
	29.2-30.1	1	-	23.7	64	40	66	44	--	88	47	1.08
	30.1-31.0	4	21.2-21.3	21.2	63	41	68	45	--	90	48	1.08
	31.0-31.6	4	21.1-21.3	21.2	64	42	68	46	--	91	48	1.10
	31.6-32.5	8	21.1-21.5	21.4	67	44	67	45	--	91	51	1.07
	32.5-33.3	4	21.2-21.7	21.5	--	--	68	46	--	87	48	--
	33.3-34.2	5	21.4-21.8	21.6	--	--	69	47	--	92	50	--

(Continued)

* Tests conducted on materials which had been dried to 105° C.

** Values in parentheses are results of liquid limits tests conducted on materials which had been dried to 105° C.

Table 1 (Concluded)

Boring No.	Depth, ft	Natural Moisture Content No. Tests	Natural Moisture Content Range	Natural Moisture Content Average	Soil Indices Tested with Distilled Water LL	Soil Indices Tested with Distilled Water PI	Net Ground Water LL	Net Ground Water PI	Grain Size Analyses Percent Finer than 0.074 mm	0.010 mm	0.002 mm	Activity Index PI/(% 0.002 mm - 10)
					Lower Pepper Shale							
8A6C-445	84.6-85.5	3	19.6-21.5	20.7	54	35	--	--	99	70	43	1.06
	85.5-87.3	2	26.0-26.3	26.2	95	69	--	--	99	92	56	1.50
	87.3-88.2	4	26.9-27.4	27.1	115	89	--	--	98	92	51	2.18
	88.2-89.1	9	26.7-27.3	27.3	103	79	--	--	100	93	54	1.80
	89.2-90.1	6	25.8-27.4	26.4	91	68	--	--	99	88	51	1.66
	90.1-91.0	7	24.9-28.2	26.4	84	60	--	--	98	86	53	1.40
	91.3-92.2	8	24.0-30.0	26.4	78(95)**	54(71)**	--	--	98	65	41	1.74(2.29)
	92.2-93.1	8	22.4-24.0	22.9	77	54	--	--	96	83	45	1.54
					Del Rio Shale							
DR-1	9.9-10.8	10	16.0-20.3	18.5	69	48	--	--	93	72	38	1.72
	10.8-11.7	8	16.5-23.3	19.6	--(68)**	--(48)**	--	--	--	--	--	--
	11.7-12.6	11	16.0-22.8	18.2	66	47	--	--	99	82	50	1.18
	12.6-13.5	6	16.7-18.9	17.0	72	50	--	--	97	72	36	1.92
DR-2	9.3-10.4	1	-	19.0	56	39	--	--	94	67	38	1.39
DR-4	11.8-12.7	8	16.5-18.4	17.6	74	51	--	--	93	64	38	1.82

** Values in parentheses are results of liquid limits tests conducted on materials which had been dried to 105° C.

Table 2

Water Analyses

Tests	Results* Ground Water	Results* Tap Water
Total solids	1275	170
Dissolved solids	1274**	170
Calcium, as Ca	2.1	23
Magnesium, as Mg	2.7	4.6
Sodium and Potassium, as Na (by difference)	553	27
Sulfates, as SO_4	0.0	44
Chlorides, as Cl	54	30
Carbonates, as CO_3	108	14
Bicarbonates, as HCO_3	1115	10
Nitrates, as NO_3	0.3	4.0
Alkalinity (phenolphthalein), as $CaCO_3$	90	12
(methyl-orange), as $CaCO_3$	1094	32
Iron, as Fe (total)	0.04	0.01
Iron, as Fe (dissolved)	0.01	0.01
Silica, as SiO_2	14	6.2
Fluoride, as F	9.5	0.60
Manganese, as Mn (total)	0.00	0.00
Manganese, as Mn (dissolved)	0.00	0.00
Total hardness, as $CaCO_3$	16	76
Carbonate hardness, as $CaCO_3$	16	32
Noncarbonate hardness, as $CaCO_3$	0	44
Free carbon dioxide, as CO_2	16	0.00
Resistivity, ohm/cm, at 25° C	660	3486
Dissolved solids, as NaCl (by conductance)	760	137
pH value	8.2	9.6

* All results are in parts per million (ppm) except the pH value.

** Computations of a hypothetical nature indicate that the chief mineral compound present in the ground water is sodium carbonate or bicarbonate; in tap water calcium carbonate, sodium chloride, and sodium or calcium sulphate are present in nearly equal amounts.

Table 3

Consolidation Tests, Upper Pepper Shale

Series No.	1				2				3		4	
Type of Inundation Water	Ground				Distilled				Distilled		Distilled	
Loading Frequency	Daily				Daily				Daily	Biweekly	Daily	
Consolidometer Ring Lining	Brass				Brass				Brass	Brass	Teflon	Greased
SWD Sample No.	M-9070				M-9076				M-9073		M-9068	
Depth, ft	27.8-28.7				32.4-33.4.				30.2-31.0		25.5-26.2	
Liquid limit	67				69				64		68	
Plastic limit	23				23				23		21	
Plasticity index	44				46				41		47	
Clay fraction (<0.002 mm)	51				53				41		40	
Initial specimen thickness, in., nominal	1/4	3/8	1/2	1	1/4	3/8	1/2	1	1/4	1	1	1
Initial specimen thickness, in., actual	0.243	0.374	0.493	0.996	0.252	0.370	0.509	0.996	0.275	1.000	1.001	1.000
Initial water content, percent	21.2	21.4	21.3	21.2	21.1	21.3	21.3	21.1	20.9	21.0	21.2	21.7
Initial dry density, pcf	106.9	108.0	108.1	107.7	107.9	107.9	107.9	108.4	107.3	107.2	108.4	108.3
Initial saturation, percent	98	102	101	100	99	100	100	100	99	99	103	105
Final water content, percent	22.6	22.2	21.6	21.9	22.8	22.0	21.9	21.9	23.0	22.3	21.1	22.0
Final dry density, pcf	108.9	108.9	108.2	106.7	108.5	109.4	108.3	107.4	106.6	106.7	107.9	107.5
Final saturation, percent	110	108	103	101	108	107	104	101	107	104	101	104
t_{50}, minutes (normalized to 1/4-in. thickness)*												
1.0-tsf load	--	--	--	--	8	--	--	--	--	--	--	--
2.0-tsf load	8	9	7	5	7	10	8	--	15	--	--	--
4.0-tsf load	17	21	19	13	18	22	23	18	25	44	16	--
8.0-tsf load	24	27	27	13	32	32	31	18	49	38	14	13
16.0-tsf load	17	18	22	6	15	20	22	12	30	--	9	9
32.0-tsf load	10	12	14	7	15	16	16	11	22	18	9	9
64.0-tsf load	11	10	11	8	11	12	12	9	16	17	9	8
Cα												
0.5-tsf load	0.0027	--	--	--	0.0016	--	--	--	--	--	--	--
1.5-tsf load	0.0027	0.0012	--	--	0.0033	0.0014	0.0009	--	0.0014	--	--	--
2.0-tsf load	0.0023	0.0017	0.0016	0.0010	0.0016	0.0016	0.0015	0.0012	0.0019	0.0014	0.0032	0.0032
4.0-tsf load	0.0023	0.0023	0.0023	0.0023	0.0025	0.0025	0.0025	0.0025	0.0051	0.0051	0.0025	0.0025
8.0-tsf load	0.0028	0.0028	0.0028	0.0028	0.0032	0.0032	0.0032	0.0032	0.0042	0.0042	0.0027	--
16.0-tsf load	0.0027	0.0027	0.0027	0.0027	0.0024	0.0024	0.0024	0.0024	0.0038	0.0026	0.0026	0.0026
32.0-tsf load	0.0027	0.0027	0.0027	0.0027	0.0024	0.0024	0.0024	0.0024	0.0031	0.0023	0.0023	0.0023
64.0-tsf load	0.0027	0.0027	0.0027	0.0027	0.0019	0.0019	0.0019	0.0019	0.0023	0.0023	0.0027	0.0027

* Reference Part II for further discussion.

Table 4

Direct Shear Tests

Thickness in.	Shear Rate	w_i percent	γ_d pcf	σ tsf	τ tsf	t_f min	Rate of Strain in./min	Depth ft
				Upper Pepper, Boring 8A6C-445				
0.25	Fast	20.0	108	1.5	0.86	16	0.005	55.4-56.2
		20.6	105	3.0	1.05	6	0.003	55.4-56.2
		19.7	108	6.0	1.87	6	0.001	55.4-56.2
	Medium	20.1	108	1.5	0.71	20	0.0001	54.5-55.4
		19.8	110	3.0	1.17	350	0.00007	54.5-55.4
		20.2	109	6.0	1.73	310	0.00006	54.5-55.4
		20.7	108	1.5	0.62	95	0.00007	50.0-50.9
	Slow	20.0	110	1.5	0.62	3,200	0.000004	50.9-51.8
		20.6	108	3.0	0.97	3,100	0.000007	50.9-51.8
		20.5	109	6.0	1.77	1,500	0.000003	52.7-53.3
0.375	Fast	20.4	109	1.5	1.17	6	0.003	53.5-54.5
		20.6	108	3.0	1.76	9	0.002	53.5-54.5
		20.2	108	6.0	2.02	13	0.003	53.5-54.5
	Medium	19.0	110	1.5	1.01	700	0.00006	54.5-55.4
		20.0	108	3.0	1.46	600	0.00007	54.5-55.4
		20.2	108	6.0	2.06	112	0.0002	54.5-55.4
		19.8	111	6.0	1.57	240	0.00008	50.0-50.9
	Slow	20.7	109	1.5	0.89	2,200	0.000004	53.5-54.5
		20.1	109	3.0	0.84	1,400	0.000004	53.5-54.5
		20.0	108	6.0	1.81	4,400	0.000004	53.5-54.5
		20.3	108	3.0	1.34	14,300	0.000001	53.5-54.5
0.5	Fast	20.2	109	1.5	1.43	15	0.006	54.5-55.4
		20.1	109	3.0	2.78	15	0.003	54.5-55.4
		20.1	109	6.0	2.79	12	0.003	54.5-55.4
		18.9	112	3.0	1.98	5	0.004	50.0-50.9
	Medium	20.1	109	1.5	1.05	460	0.00007	53.5-54.5
		20.6	109	3.0	1.98	900	0.00008	53.5-54.5
		20.6	109	6.0	2.72	300	0.00008	53.5-54.5
	Slow	16.7	115	1.5	1.35	10,000	0.000004	50.9-51.8
		16.9	115	3.0	1.98	5,700	0.000005	50.9-51.8
		18.1	113	6.0	2.91	11,000	0.000004	50.9-51.8

(Continued)

Table 4 (Continued)

Thickness in.	Shear Rate	w_i percent	γ_d pcf	σ tsf	τ tsf	t_f min	Rate of Strain in./min	Depth ft
				Upper Pepper, Boring 8A6C-445 (Continued)				
1.0	Fast	20.5	108	1.5	1.65	8	0.004	50.0-50.9
		20.5	108	3.0	2.76	10	0.003	50.0-50.9
		19.0	109	6.0	3.60	16	0.003	50.0-50.9
	Medium	20.2	108	1.5	1.99	340	0.00008	52.7-53.3
		19.7	110	3.0	2.74	480	0.00008	52.7-53.3
		20.0	109	6.0	2.45	270	0.00009	50.9-51.8
		20.0	109	1.5	1.88	410	0.00009	55.4-56.2
		20.0	110	3.0	2.66	1,700	0.00004	55.4-56.2
		20.2	109	6.0	3.63	1,500	0.00004	55.4-56.2
	Slow	19.7	109	1.5	1.70	3,100	0.000004	52.7-53.3
		20.3	109	3.0	2.18	4,900	0.000005	50.9-51.8
		20.2	108	6.0	2.11	2,900	0.000006	50.9-51.8
		20.0	110	6.0	3.25	21,500	0.000002	51.8-52.7
		19.0	111	1.5	2.02	29,100	0.000002	51.8-52.7
				Upper Pepper, Borings 8A6C-446 and -447				
1.0	Medium	21.6	107	1.5	1.31	75	0.0001	33.3-34.2
		21.2	108	1.5	1.44	1,200+	0.00009	32.5-34.2
		21.5	107	1.5	1.55	420	0.0002	31.6-32.5
		21.6	108	3.0	1.81	75	0.00008	33.3-34.2
		21.4	107	3.0	1.90	480	0.0002	31.6-32.5
		21.6	105	6.0	2.51	320	0.0002	32.4-33.4
		21.3	107	6.0	2.56	250	0.0002	31.6-32.5
		21.2	108	6.0	2.72	700±	0.00008	32.5-33.3
		21.4*	106	6.0	2.81	320	0.0002	32.4-33.4
	Fast	21.8	106	18.0	4.76	40	0.002	33.3-34.2
		21.7	107	18.0	4.76	35	0.001	33.5-33.3
	Slow	21.7	107	18.0	4.26	18,000	0.000004	32.5-33.3
		21.6	107	18.0	4.49	13,270	0.000004	32.5-33.3
	Fast	21.4	107	12.0	3.61	28	0.002	33.3-34.2

(Continued)

* This inundation fluid was tap water; on all other tests ground water was used.

Table 4 (Continued)

Thickness in.	Shear Rate	w_i percent	γ_d pcf	σ tsf	τ tsf	t_f min	Rate of Strain in./min	Depth ft
				Lower Pepper, Boring 8A6C-445				
0.25	Fast	22.4	99	1.5	0.63	5	0.006	92.2-93.1
		23.0	105	3.0	1.00	4	0.005	92.2-93.1
		24.0	105	6.0	1.99	4	0.003	92.2-93.1
	Medium	28.7	97	1.5	0.25	7	0.0004	90.1-91.0
		28.2	96	3.0	0.61	200	0.00008	90.1-91.0
		27.6	98	6.0	1.50	200	0.00009	90.1-91.0
		23.0	105	1.5	0.45	90	0.00007	92.3-93.1
	Slow	26.0	100	1.5	0.52	1,600	0.000004	86.5-87.3
		26.4	98	3.0	0.83	8,800	0.000003	89.2-90.1
		26.2	99	6.0	1.23	1,000	0.000004	89.2-90.1
0.375	Fast	27.0	98	1.5	0.83	5	0.003	88.2-89.1
		26.8	98	3.0	1.13	8	0.003	88.2-89.1
		27.8	97	6.0	2.16	8	0.002	88.2-89.1
	Medium	26.7	99	1.5	0.59	800	0.00007	88.2-89.1
		27.8	98	3.0	0.83	240	0.00008	88.2-89.1
		27.1	98	6.0	1.44	360	0.00008	88.2-89.1
	Slow	26.2	98	1.5	0.75	5,700	0.000005	89.2-90.1
		26.4	99	3.0	0.79	2,800	0.000007	89.2-90.1
		30.1	91	6.0	1.11	10,000	0.000004	91.3-92.2
0.5	Fast	24.8	101	1.5	0.95	3	0.004	91.3-92.2
		25.1	101	3.0	1.80	6	0.004	91.3-92.2
		25.4	100	6.0	1.95	4	0.004	91.3-92.2
	Medium	26.1	99	1.5	0.44	75	0.00008	89.2-90.1
		25.8	97	3.0	0.62	500	0.00008	89.2-90.1
		26.1	99	6.0	1.80	380	0.00008	89.2-90.1
		24.6	102	1.5	1.00	200	0.00007	91.3-92.2
		24.6	102	3.0	1.42	95	0.00008	91.3-92.2
		24.6	102	6.0	2.24	330	0.00008	91.3-92.2
	Slow	27.8	97	1.5	0.93	2,400	0.000004	88.2-89.1
		27.8	98	3.0	0.60	300	0.000001	88.2-89.1
		27.3	97	6.0	1.76	13,000	0.000003	86.2-89.1

(Continued)

Table 4 (Continued)

Thickness in.	Shear Rate	w_i percent	γ_d pcf	σ tsf	τ tsf	t_f min	Rate of Strain in./min	Depth ft
		Lower Pepper, Boring 8A6C-445 (Continued)						
1.0	Fast	21.5	106	1.5	1.81	7	0.003	84.6-85.5
		21.0	108	3.0	2.78	9	0.001	85.6-85.5
		23.5	104	6.0	2.18	10	0.004	92.2-93.1
	Medium	26.7	99	1.5	1.50	60	0.0001	89.2-90.1
		26.3	99	3.0	1.34	250	0.00009	86.5-87.3
		25.1	102	6.0	1.80	600	0.00008	90.1-91.0
		24.0	104	6.0	2.02	500	0.00008	91.3-92.2
		22.7	106	1.5	1.33	1,400	0.00006	92.2-93.1
		27.4	99	6.0	1.70	440	0.00008	89.2-90.1
	Slow	25.2	102	1.5	0.42	1,500	0.000006	90.1-91.0
		24.9	102	3.0	1.85	6,600	0.000004	90.1-91.0
		24.8	102	6.0	2.26	5,700	0.000003	90.1-91.0
		21.8	107	1.5	0.79	25,800	0.000001	92.2-93.1
		Del Rio, Borings DR-1 and DR-4						
0.25	Fast	18.8	111	1.5	0.94	18	0.005	11.7-12.7
		22.8	102	3.0	1.25	7	0.003	11.7-12.7
		16.7	116	6.0	2.54	10	0.003	12.7-13.5
	Medium	20.2	109	1.5	0.66	45	0.0001	9.9-10.8
		20.3	110	3.0	1.31	180	0.00007	9.9-10.8
		19.1	112	6.0	2.00	420	0.00009	9.9-10.8
		18.4	113	1.5	0.91	120	0.00007	11.8-12.7
	Slow	17.5	115	1.5	0.97	14,000	0.000005	12.7-13.5
		17.1	114	3.0	1.46	4,200	0.000006	12.7-13.5
		17.0	117	6.0	2.12	4,800	0.000005	12.7-13.5
0.375	Fast	17.7	111	1.5	1.40	9	0.005	10.8-11.7
		15.5	116	3.0	2.08	10	0.004	10.8-11.7
		18.9	110	6.0	2.79	9	0.003	12.7-13.5
	Medium	17.2	116	1.5	1.28	150	0.00009	11.7-12.7
		17.5	115	3.0	2.16	190	0.00009	11.7-12.7
		17.2	114	6.0	3.15	400	0.00009	11.7-12.7
	Slow	17.5	113	1.5	1.26	5,700	0.000004	12.7-13.5
		18.2	113	3.0	1.98	7,300	0.000004	12.7-13.5
		17.6	114	6.0	2.82	11,000	0.000004	12.7-12.5

(Continued)

Table 4 (Concluded)

Thickness in.	Shear Rate	w_i percent	γ_d pcf	σ tsf	τ tsf	t_f min	Rate of Strain in./min	Depth ft
		Del Rio, Borings DR-1 and DR-4 (Continued)						
0.5	Fast	18.0	113	1.5	1.64	11	0.004	10.8-11.7
		17.2	116	3.0	2.46	25	0.004	10.8-11.7
		20.9	108	6.0	4.38	20	0.004	10.8-11.7
	Medium	21.6	106	1.5	0.46	16	0.0002	10.8-11.7
		22.3	105	3.0	1.78	280	0.0001	10.8-11.7
		22.6	105	6.0	2.51	100	0.0002	10.8-11.7
		16.0	119	1.5	2.33	280	0.00008	9.9-10.8
	Slow	19.1	111	1.5	1.29	4,200	0.000006	9.9-10.8
		19.2	112	3.0	1.23	2,900	0.00001	9.9-10.8
		17.7	113	6.0	3.28	4,000	0.000006	9.9-10.8
		17.5	114	3.0	2.41	2,900	0.000003	11.8-12.7
1.0	Fast	16.0	115	1.5	3.02	20	0.002	11.7-12.7
		17.1	113	3.0	1.87	2	0.020	11.7-12.7
		18.1	113	6.0	3.54	16	0.002	11.7-12.7
		16.8	110	1.5	3.26	9	0.005	11.8-12.7
	Medium	17.3	115	1.5	1.28	55	0.0002	9.9-10.8
		18.5	113	3.0	3.73	150	0.0001	9.9-10.8
		17.3	115	6.0	3.58	160	0.0002	9.9-10.8
		16.5	115	3.0	2.74	300	0.00008	11.8-12.7
		19.0	111	1.5	1.61	270	0.00006	9.5-10.4
	Slow	17.8	112	1.5	1.33	4,400	0.000003	11.7-12.7
		18.9	113	3.0	2.49	4,300	0.000005	11.7-12.7
		17.1	113	6.0	4.14	13,000	0.000004	11.7-12.7

Table 5

Direct Shear Tests, Upper Pepper Shale Specimen

Thickness = 1.0 in., Medium Rate of Shear

Boring No.	Depth, ft	Test No.	w_i percent	γ_d pcf	σ tsf	τ tsf	t_f min	LL percent
			High Activity					
8A6C-445	55.4-56.2	1	20.0	109	1.5	1.88	410	--
	55.4-56.2	2	20.0	110	3.0	2.66	1700	--
	55.4-56.2	3	20.2	109	6.0	3.63	1500	--
	52.7-53.3	1	20.2	108	1.5	1.99	340	86
	52.7-53.3	2	19.7	110	3.0	2.74	480	86
	50.9-51.8	3	20.0	109	6.0	2.45	270	82
			Low Activity					
8A6C-447	33.3-34.2	1	21.6	107	1.5	1.31	75	69
	32.5-33.3	2	21.2	108	1.5	1.44	1200±	68
	31.6-32.5	3	21.5	107	1.5	1.55	420	67
	33.3-34.2	4	21.6	108	3.0	1.81	75	69
	31.6-32.5	5	21.4	107	3.0	1.90	480	67
8A6C-446	32.4-33.4	6	21.6	105	6.0	2.51	320	69
8A6C-447	31.6-32.5	7	21.3	107	6.0	2.56	250	67
	32.5-33.3	8	21.2	108	6.0	2.72	700±	68
8A6C-446	32.4-33.4	9*	21.4	106	6.0	2.81	320	69

* In test 9, the inundation fluid was tap water; in all other tests ground water was used.

Table 6

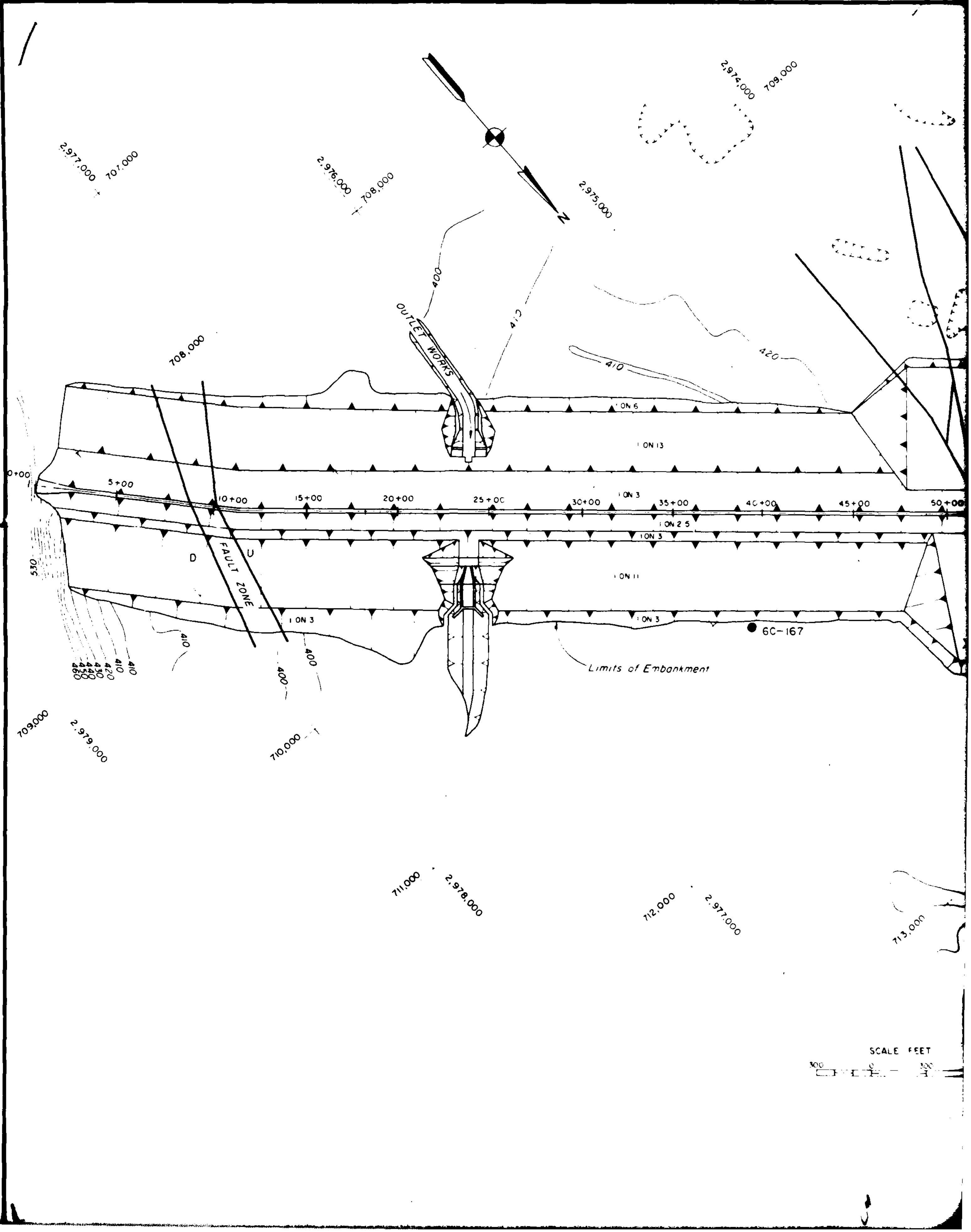
Triaxial Tests, Upper Pepper Shale

Test No.	SWD Sample No.	Orientation of Bedding Planes, deg	Specimen	w_i	γ_i	S_i	Before Test σ_{ch} tsf	Before Test t_c hr	Before Test u tsf	At Failure $\sigma_1 - \sigma_3$ tsf	At Failure u tsf	At Failure $\bar{\sigma}_3$ tsf	At Failure Strain percent	At Failure t_f min	At Failure s_{ff}	At Failure θ deg
							Q_n (Constant Strain)									
1	M-9097	60	A	21.2	108	101	1.52	46	1.10	4.66	1.10	0.42	0.5	20	2.0	59
			B	21.3	108	101	3.04	22	0.94	4.13	1.99	1.05	0.6	18	1.8	58
			C	21.2	108	101	5.93	21	3.20	5.18	4.53	1.40	0.6	15	2.4	56
			D	21.1	108	101	12.07	43	9.17	6.41	12.03	0.03	0.6	17	3.0	54
2	M-9098	45	A	21.2	109	101	1.54	23	0.05	4.32	0.18	1.36	0.6	18	1.7	52
			B	21.3	108	100	3.03	66	0.99	3.45	1.45	1.58	0.5	13	2.1	45
			C	21.1	109	100	6.03	67	3.62	3.44	5.13	0.87	0.5	11	2.1	45
			D	21.2	109	101	11.96	22	8.59	4.28	11.13	0.82	0.5	12	1.7	52
3	M-9095	45	A	21.0	107	97	1.53	43	-0.15	2.11	-0.14	1.67	3.3	55	0.8	24*
										2.86	0.17	1.36	8.8	147	1.4	45**
			B	21.1	107	97	3.05	46	1.02	2.24	1.61	1.44	3.7	61	1.0	32*
										3.29	2.37	0.69	6.6	107	1.5	58**
			C	21.0	107	97	5.94	73	4.59	2.04	4.73	1.21	3.7	58	0.9	33*
										3.42	4.83	1.11	7.7	119	1.4	64**
			D	21.0	107	98	12.13	42	9.62	5.17	12.18	-0.05	0.7	16	2.5	52**
							Q_{ss} (Stress Control)									
1	M-9074	60	A	21.1	109	100	1.58	46	0.18	3.86	1.49	0.18	0.5	47	1.7	60
			B	21.3	108	98	3.11	43	0.97	3.38	2.71	0.44	0.4	43	1.4	62
			C	21.3	108	100	6.04	45	3.62	4.49	4.75	1.29	0.9	55	1.9	62
			D	21.4	108	99	12.03	41	9.31	3.42	11.27	0.76	0.3	43	1.4	62
2	M-9099	45	A	21.4	107	99	1.48	67	0.46	2.03	0.94	0.61	0.5	34	1.0	45
			B	21.4	108	100	3.03	67	1.41	1.54	2.96	0.06	8.2	48	0.8	38
			C	21.2	108	100	6.00	66	3.92	3.56	6.06	-0.09	0.4	40	1.0	44
			D	21.5	108	101	12.16	112	9.38	2.38	10.59	1.66	7.2	41	1.1	38

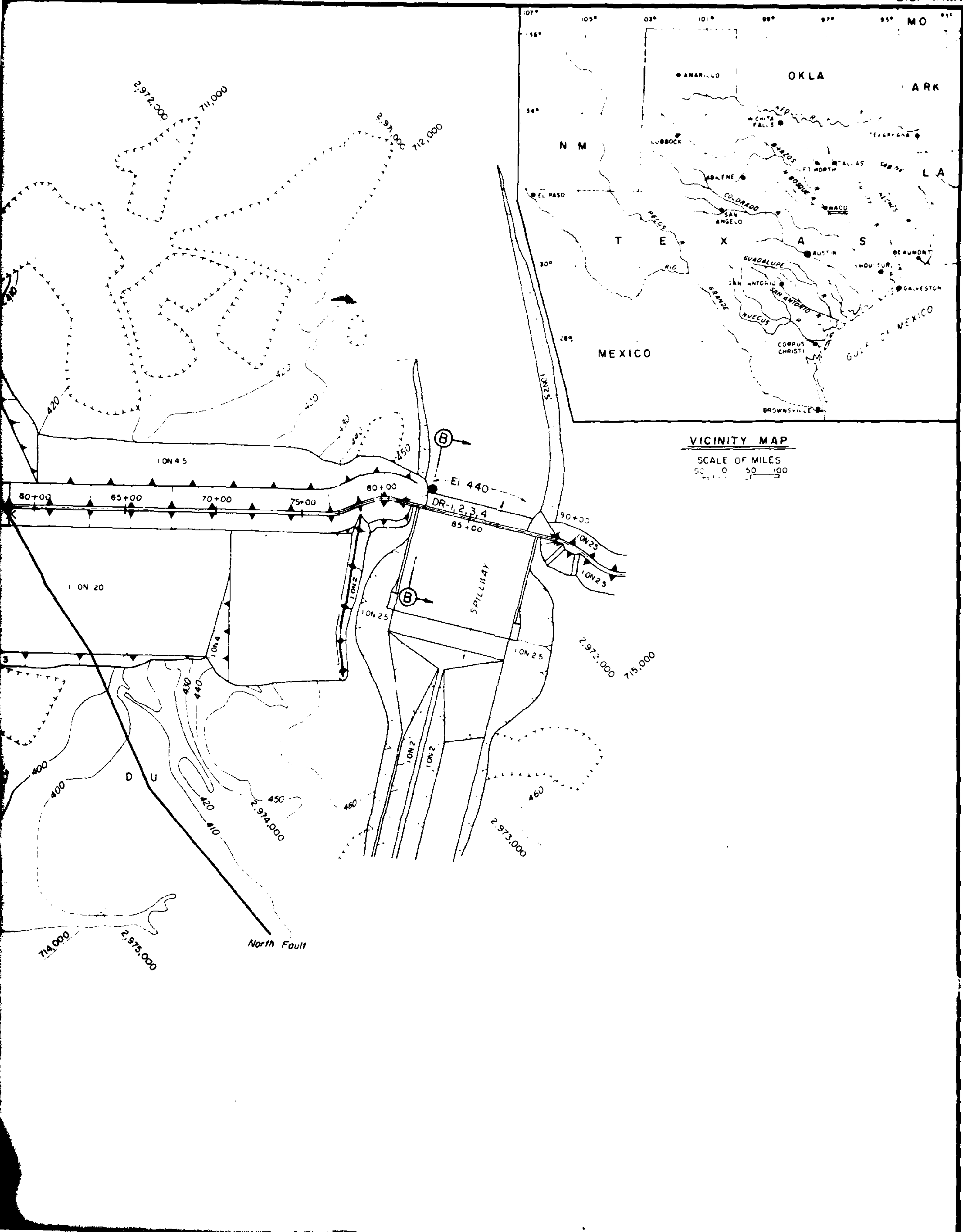
* Values observed for the initial failure along a visible joint.

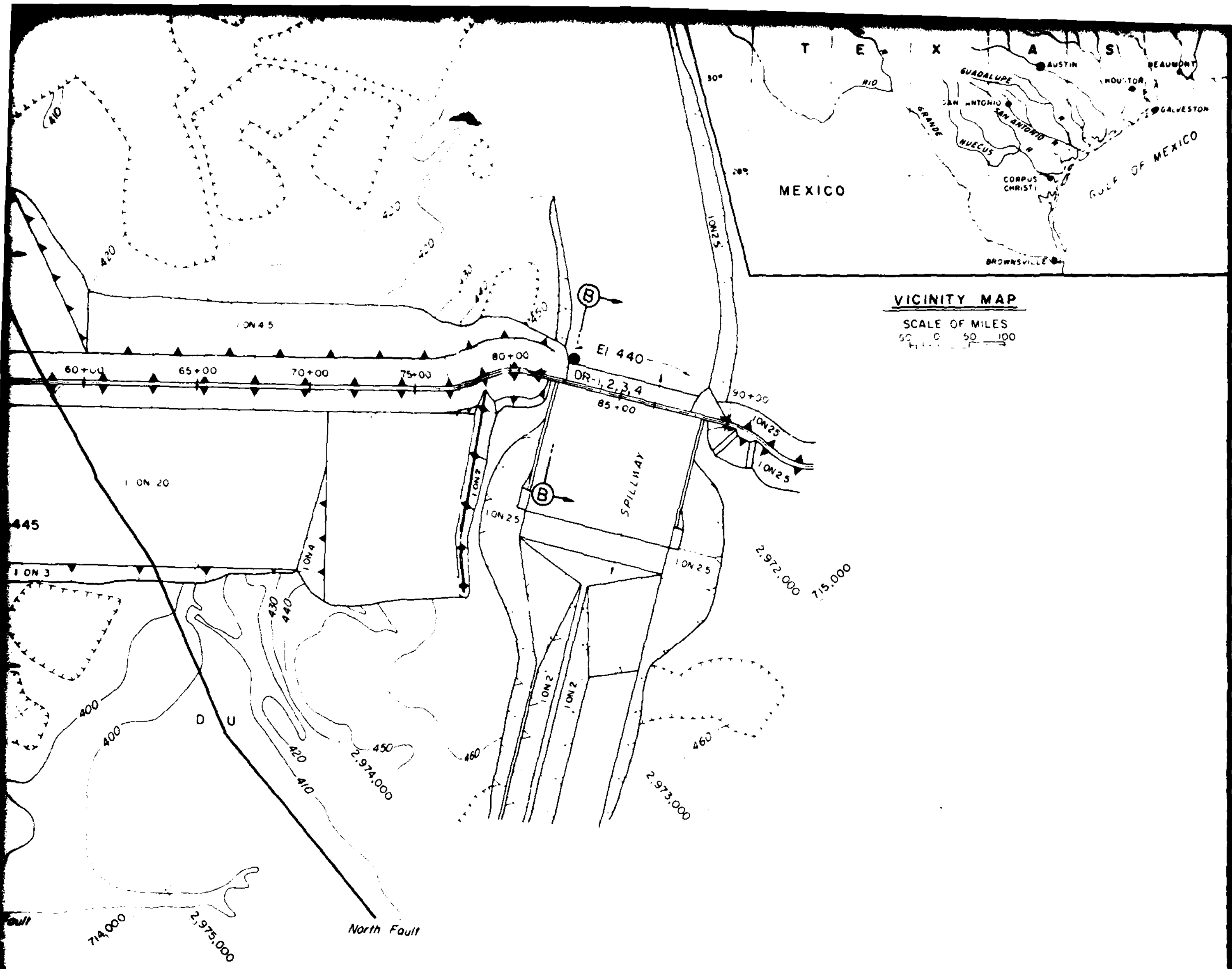
** Secondary failure. In Test D the joint intersected the end of the specimen, and no movement occurred along the joint.

CORPS OF ENGINEERS



2,973,000
710,000
2,972,000
711,000
712,000
410
420
430
440
450
460
400
1 ON 3
1 ON 4.5
1 ON 20
1 ON 4
1 ON 2
1 ON 2.5
1 ON 25
A
B
8A 6C-352
8A6C-354
8A6C-445
8A6C-446
8A6C-447
50+00
55+00
60+00
65+00
70+00
75+00
80+00
85+00
90+00
El 440
DR-1,2,3,4
SPILLWAY
D
U
2,974,000
2,973,000
715,000
713,000
714,000
2,975,000
2,976,000
South Fault
North Fault
SCALE FEET
0
300
600
N M
T E X
MEXICO
AMARILLO
LUBBOCK
ABILENE
EL PASO
SAN ANGELO
PECOS
GRANDE
107°
105°
36°
34°
30°
28°
VICINI
SCALE


VICINITY MAP
SCALE OF MILES
OKLA
ARK
MO
N.M.
LA
T E X A S
MEXICO
GULF OF MEXICO
AMARILLO
WICHITA FALLS
LUBBOCK
TEXARKANA
DALLAS
FT. WORTH
ABILENE
EL PASO
WACO
SAN ANGELO
AUSTIN
BEAUMONT
HOUSTON
GALVESTON
SAN ANTONIO
CORPUS CHRISTI
BROWNSVILLE
SPILLWAY
DR-1, 2, 3, 4
El 440
1 ON 20
1 ON 45
1 ON 25
1 ON 2
1 ON 4
60+00
65+00
70+00
75+00
80+00
85+00
90+00
North Fault
2,972,000
711,000
712,000
715,000
2,973,000
2,974,000
2,975,000
714,000



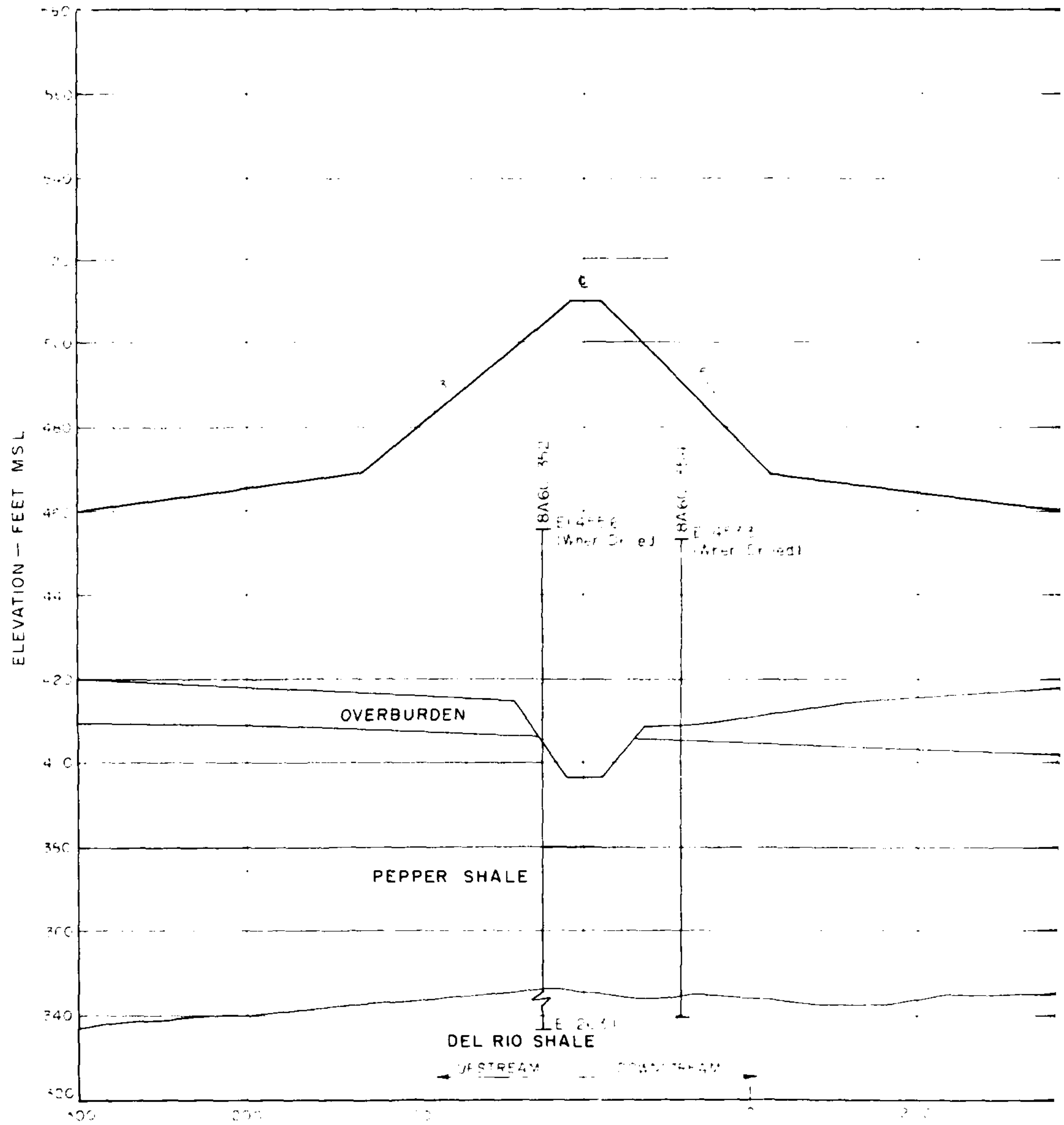
SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529

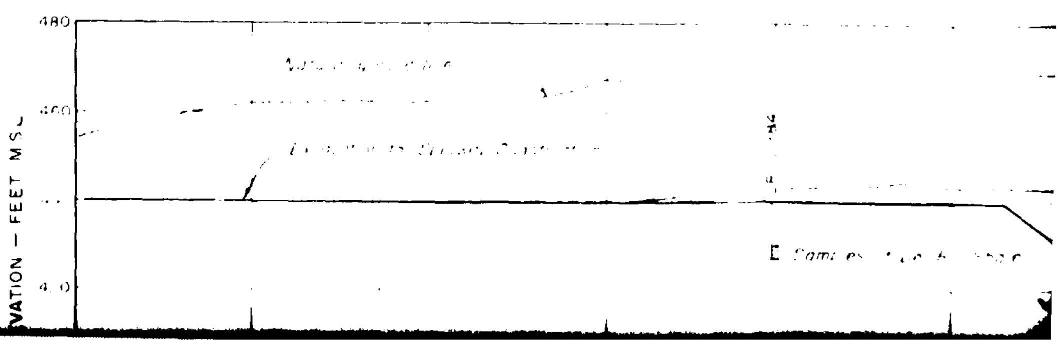
BORING LOCATIONS

U.S. ARMY ENGINEER DISTRICT, FORT WORTH

4

PLATE 1


ELEVATION — FEET MSL
OVERBURDEN
PEPPER SHALE
DEL RIO SHALE
UPSTREAM
DOWNSTREAM
℄


480
VATION — FEET MSL

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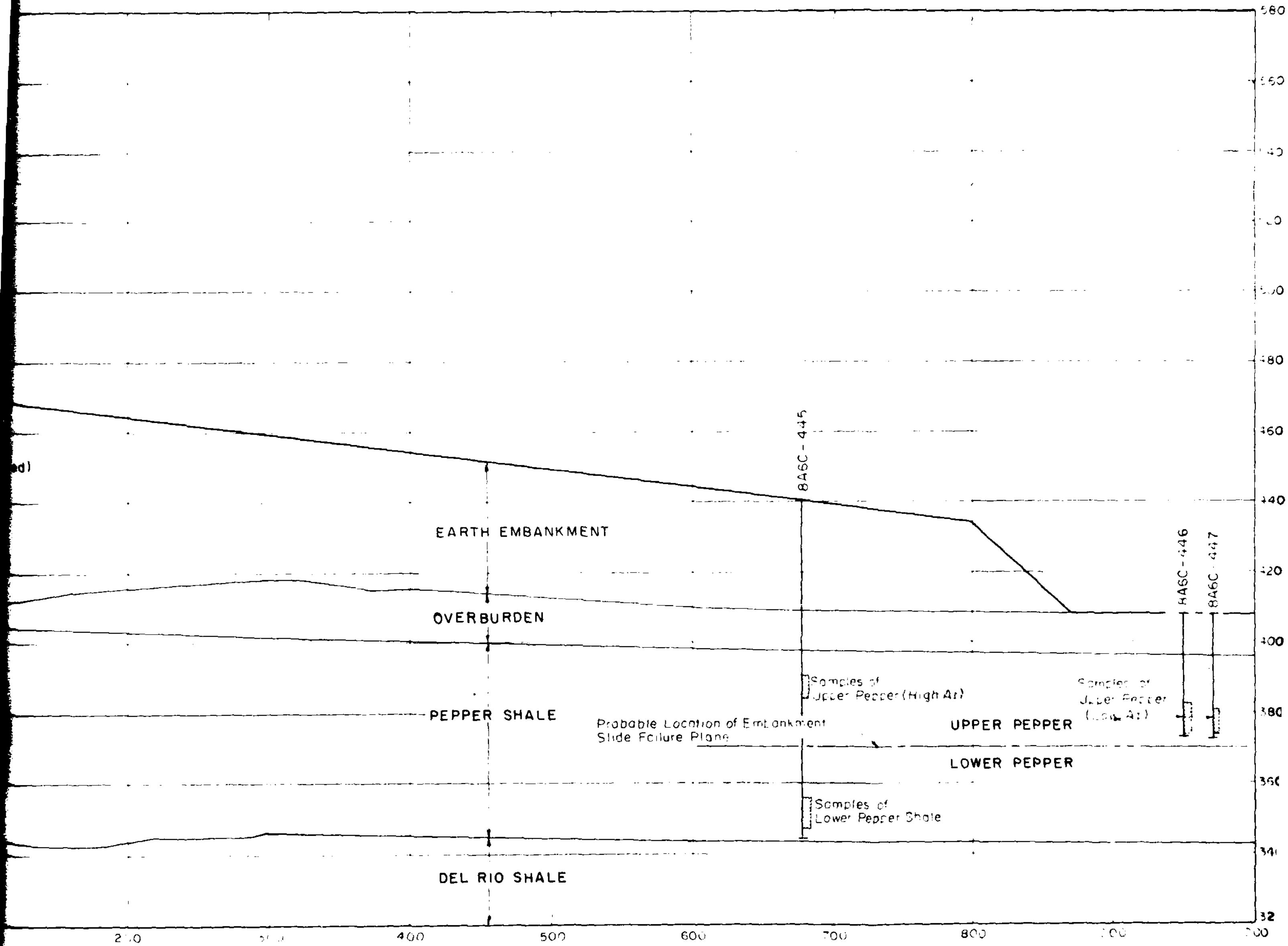
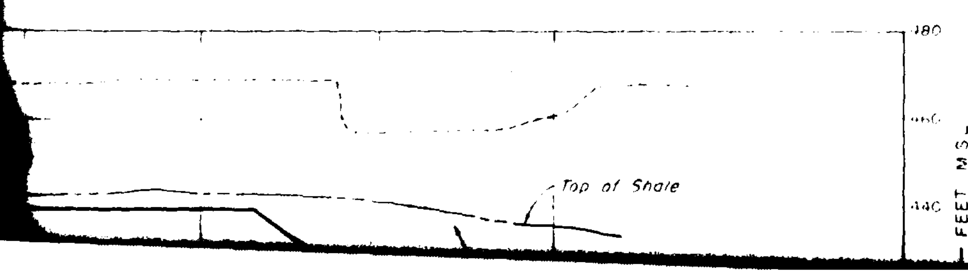
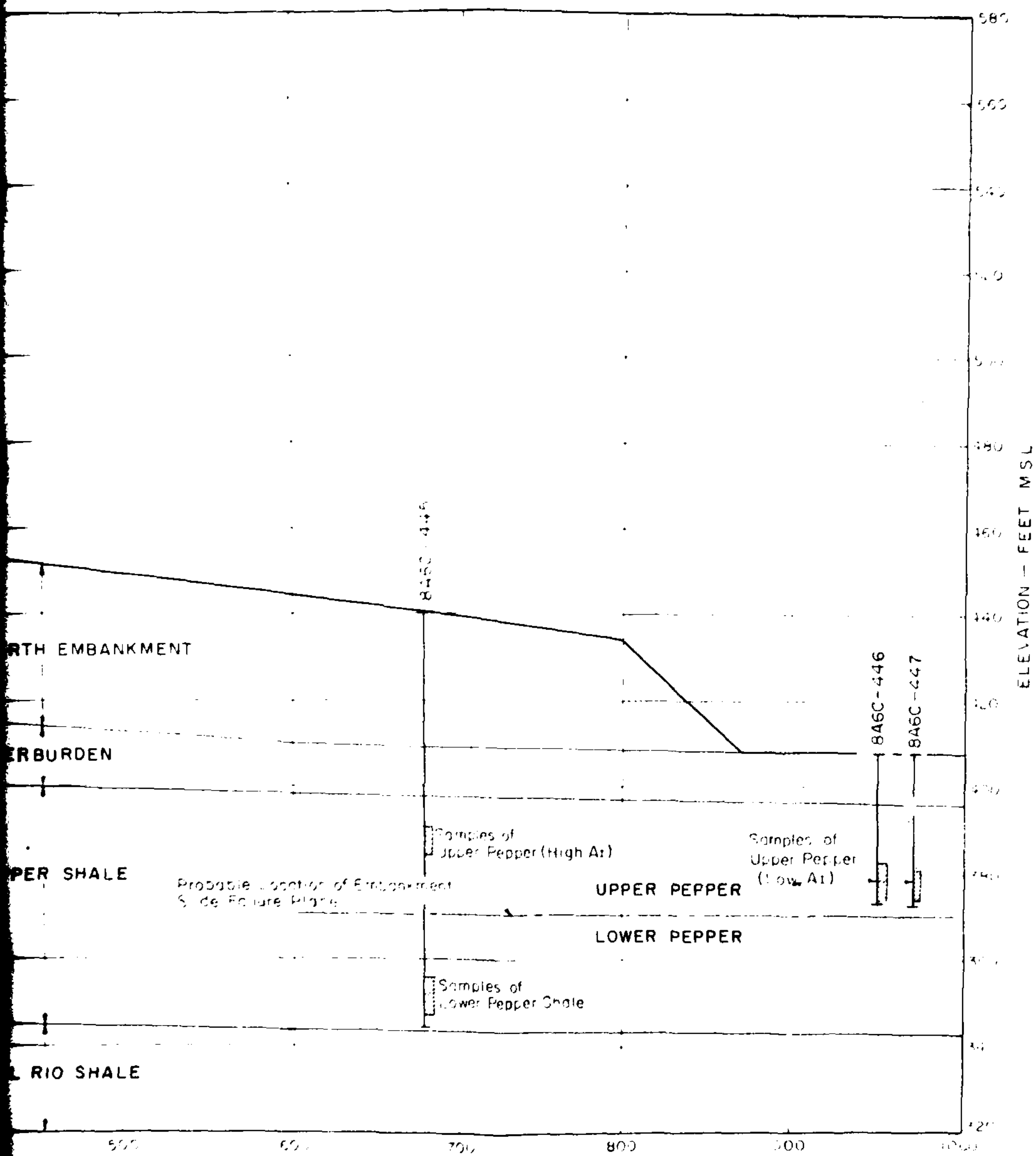


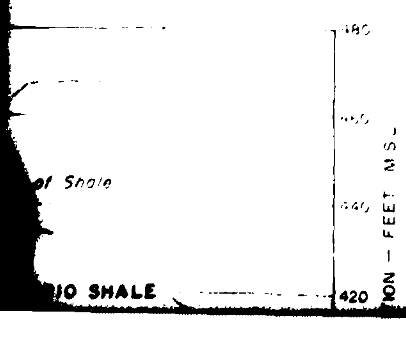
SECTION A-A



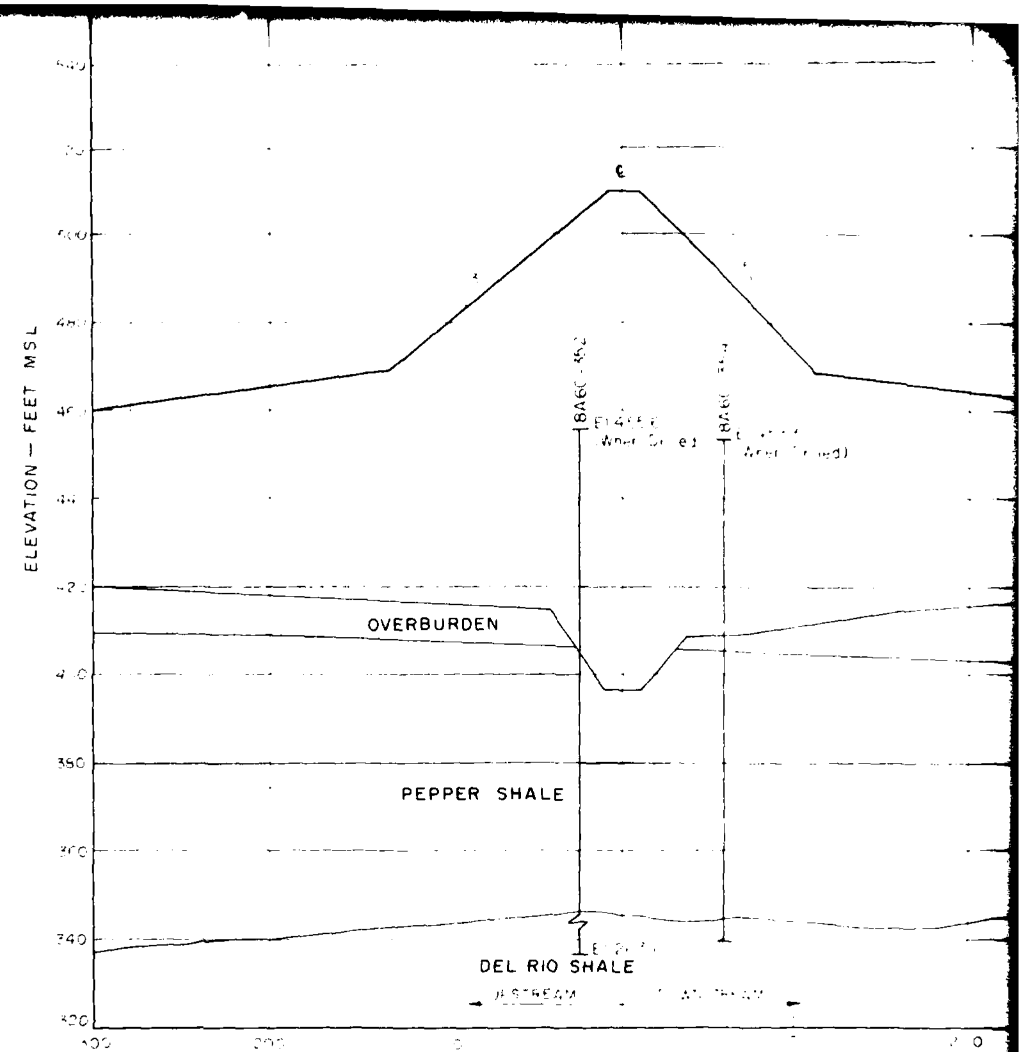
Note
See Pl
Sections A

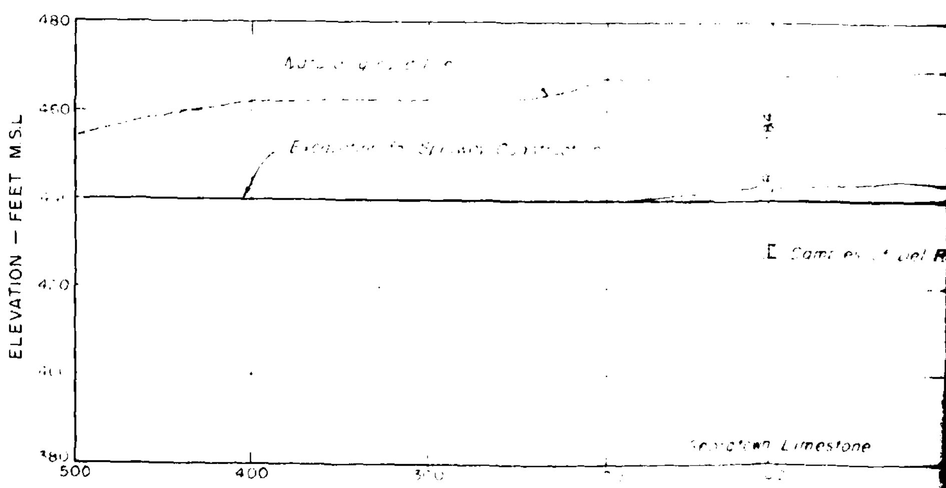
US ARMY





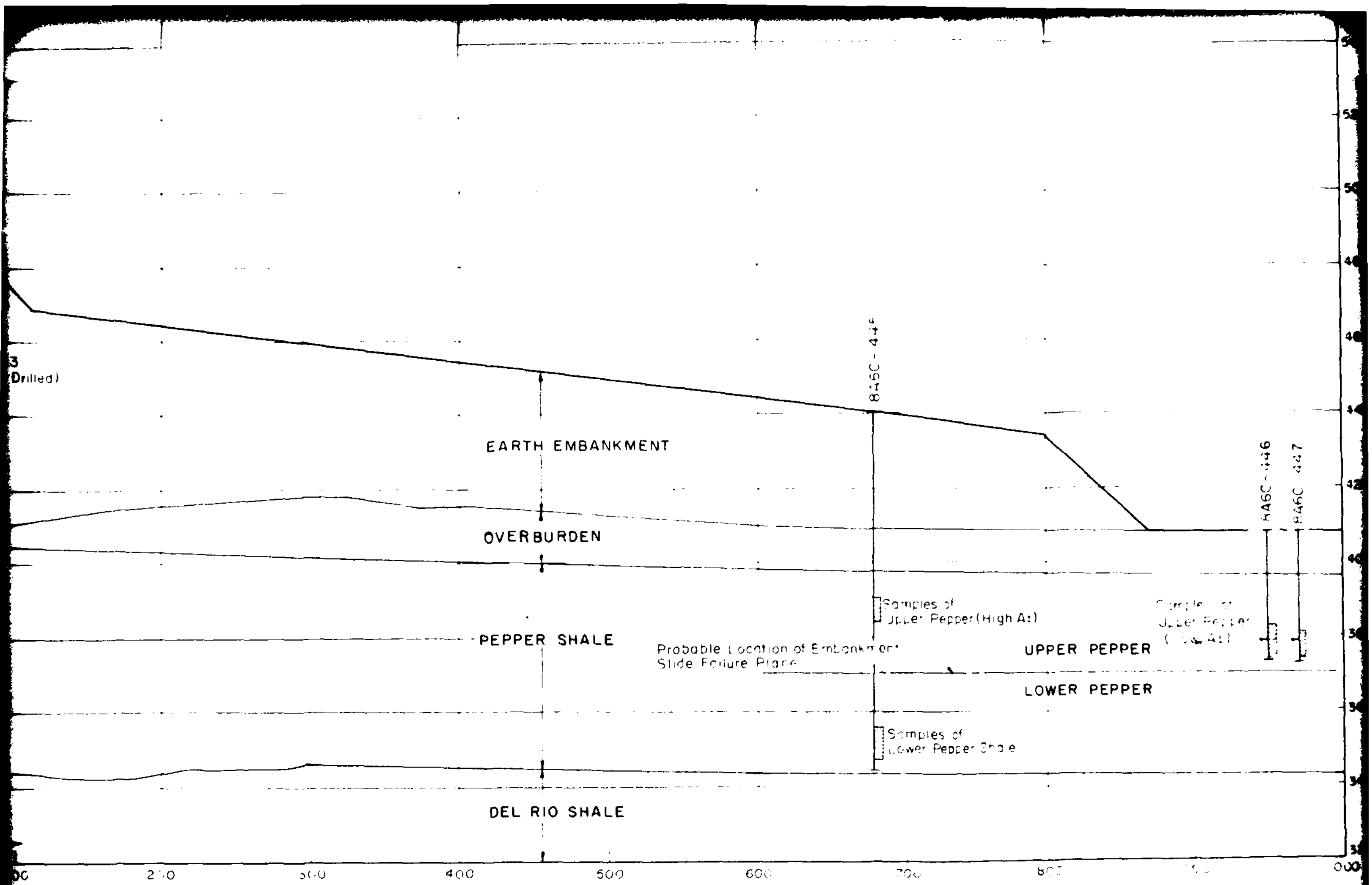
Note
See Plate ... location of Sections A-A and B-B


ELEVATION — FEET MSL
℄
OVERBURDEN
PEPPER SHALE
DEL RIO SHALE
380
340
320

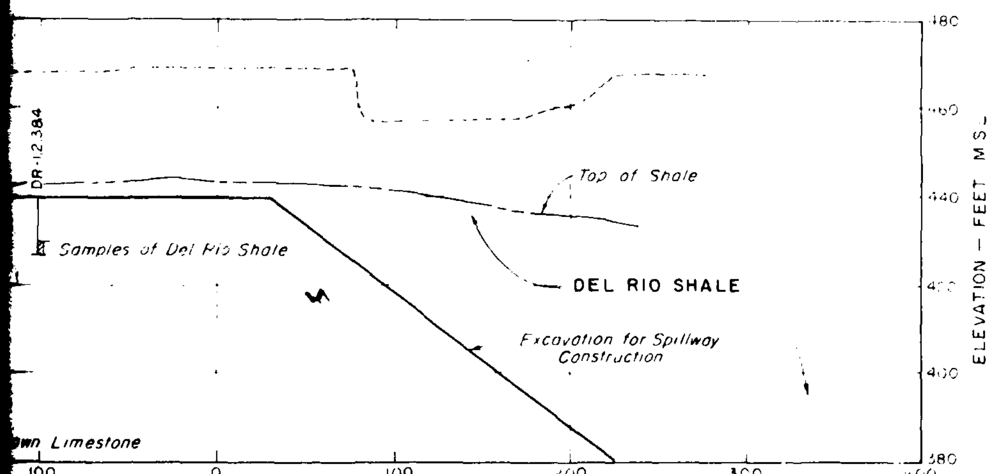

ELEVATION — FEET MSL
480
460
380
500
400

SECTION B-

4



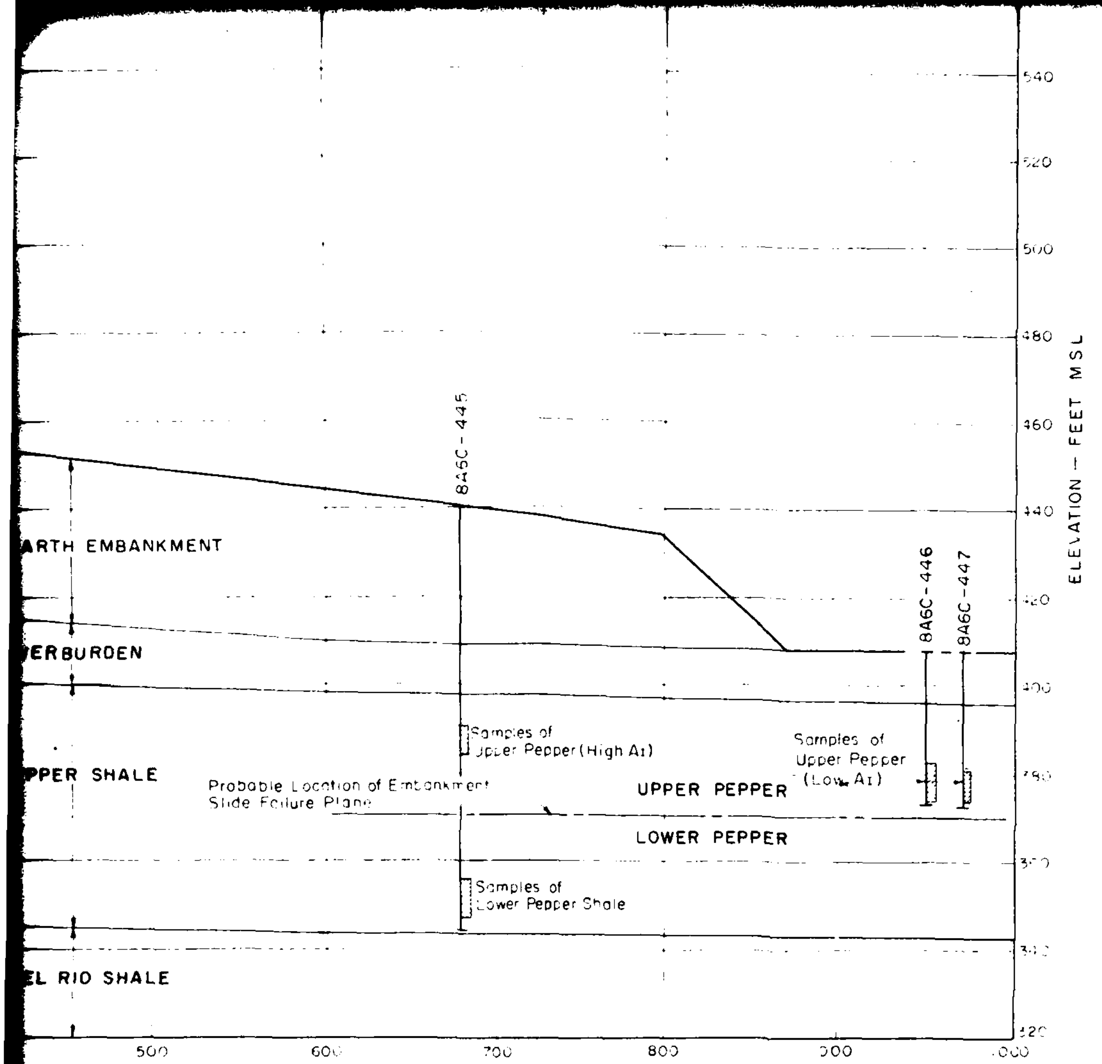
SECTION A-A

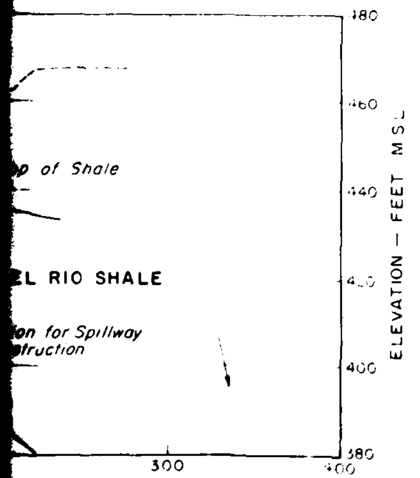


SECTION B-B

Note
See Pl
Sections A

US ARMY





Note
See Plate 1 for Location of Sections A-A and B-B

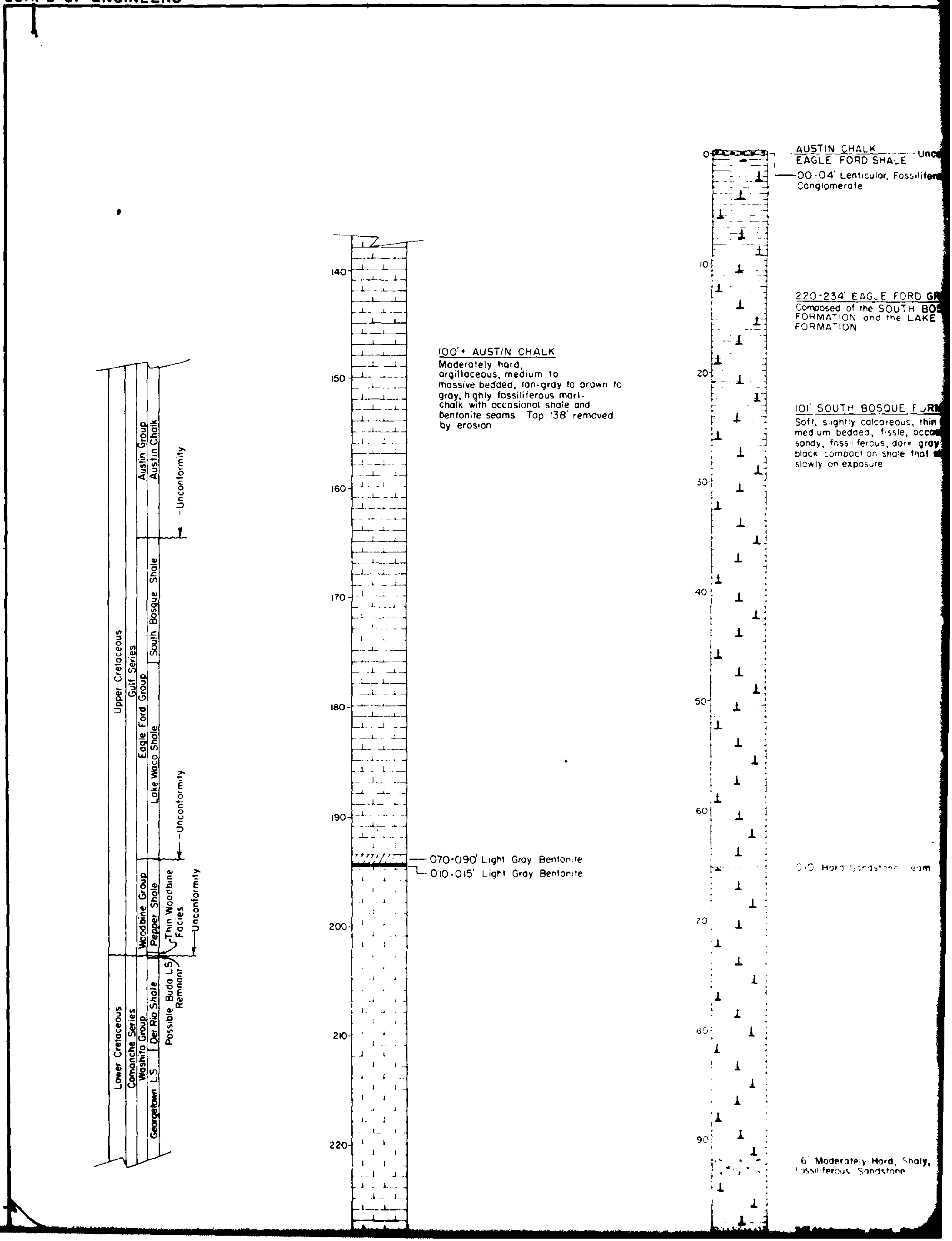
SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529

LOCATIONS OF SAMPLES

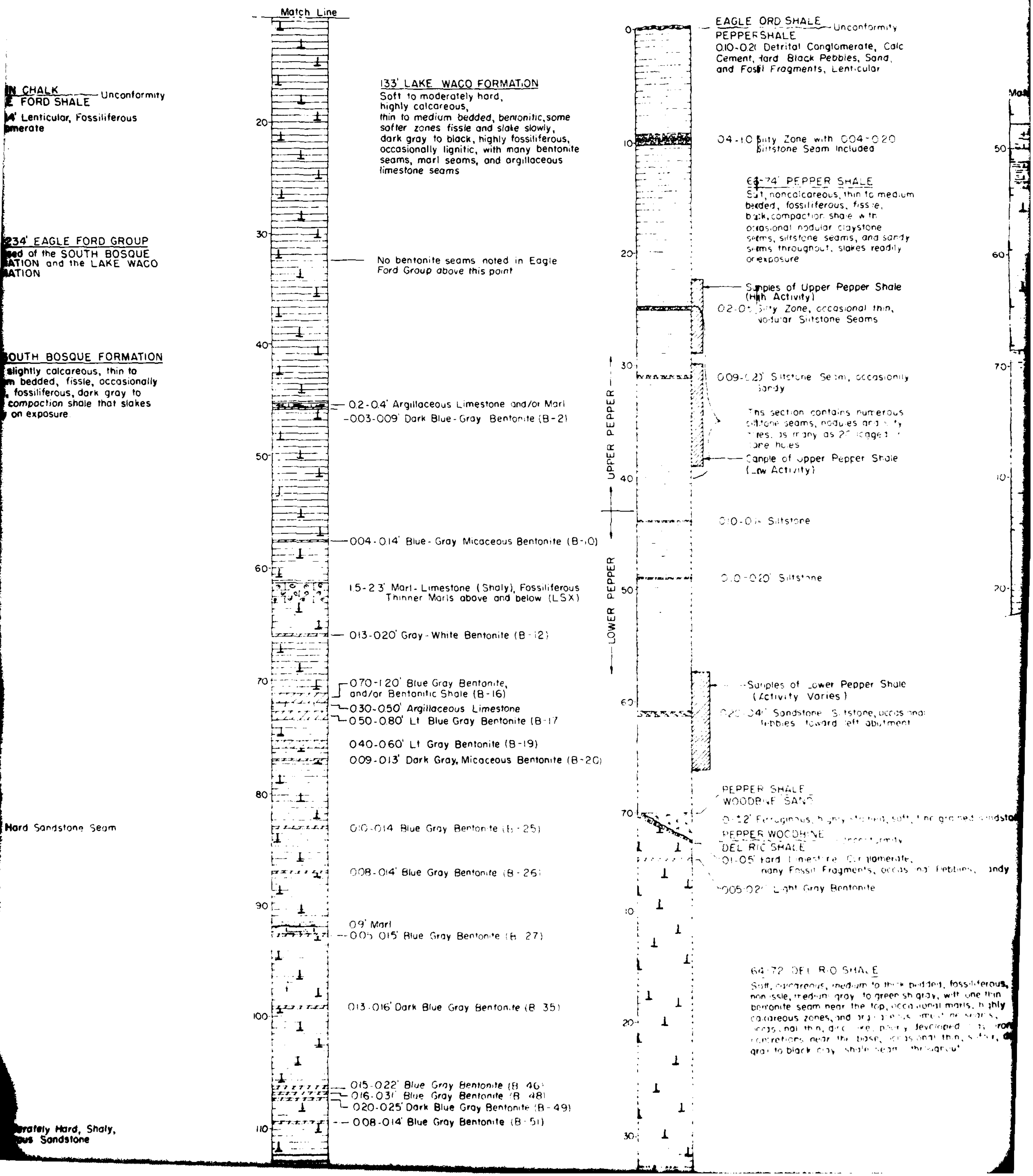
U S ARMY ENGINEER DISTRICT, FORT WORTH

PLATE 2

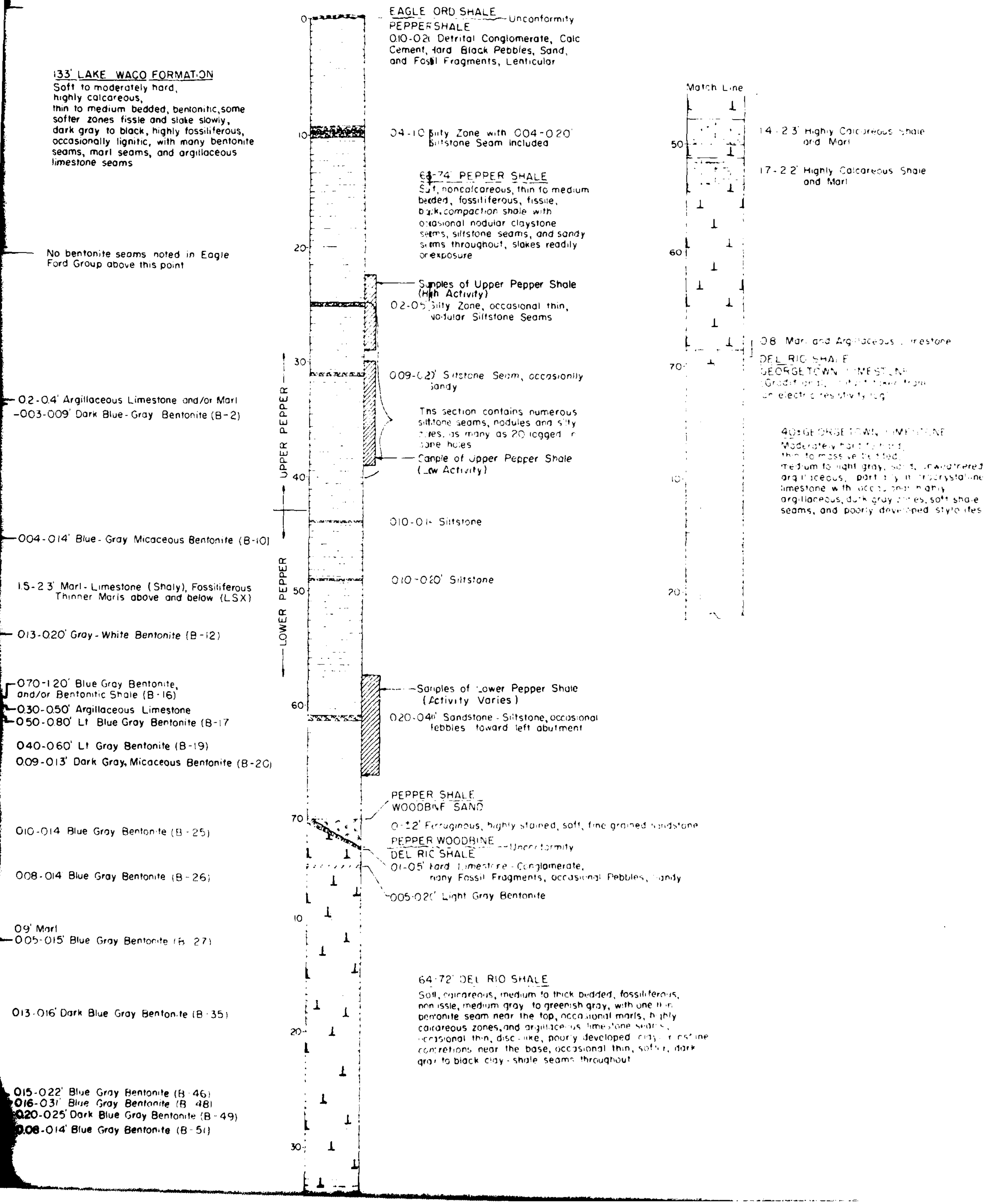
CORPS OF ENGINEERS

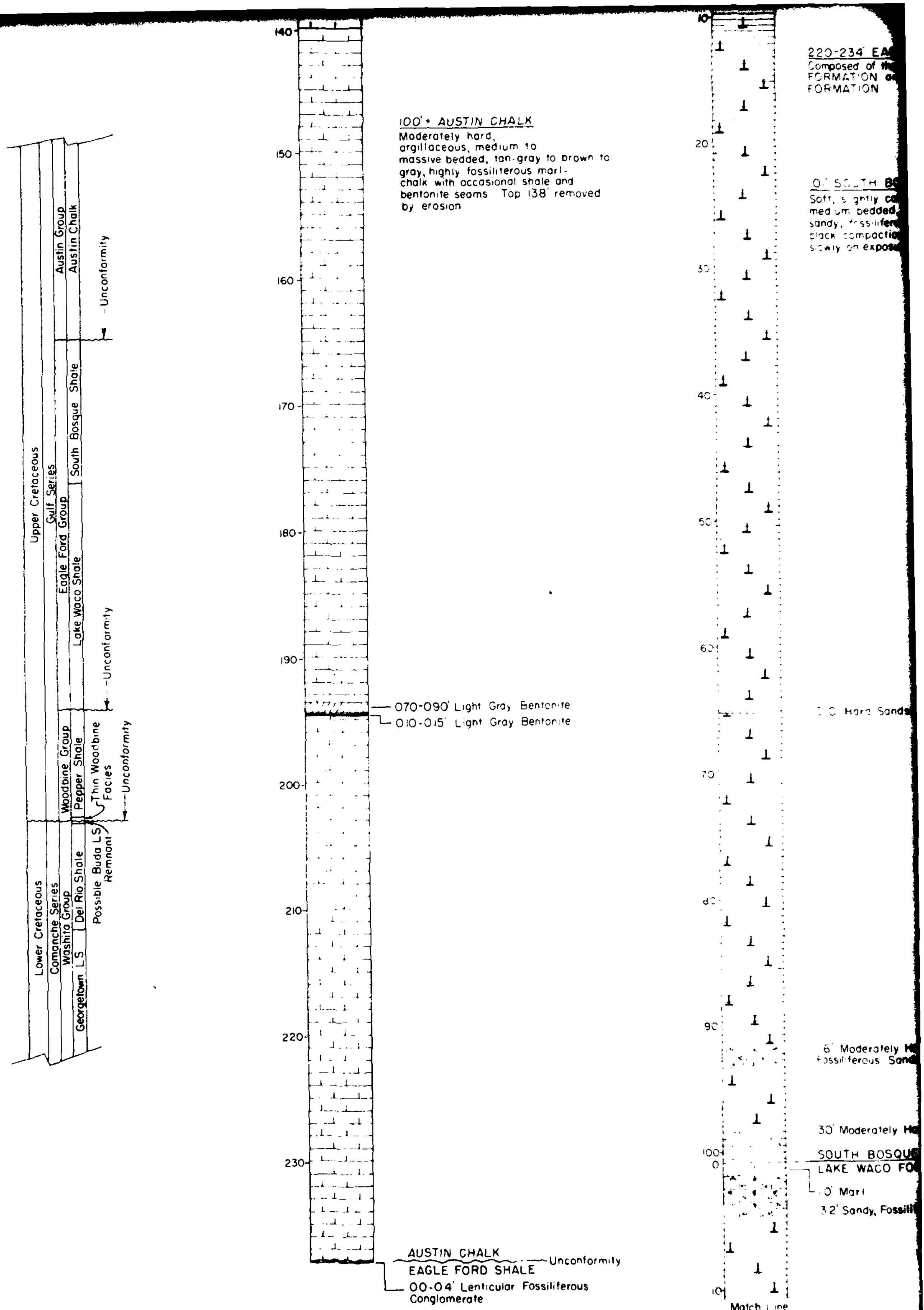


12

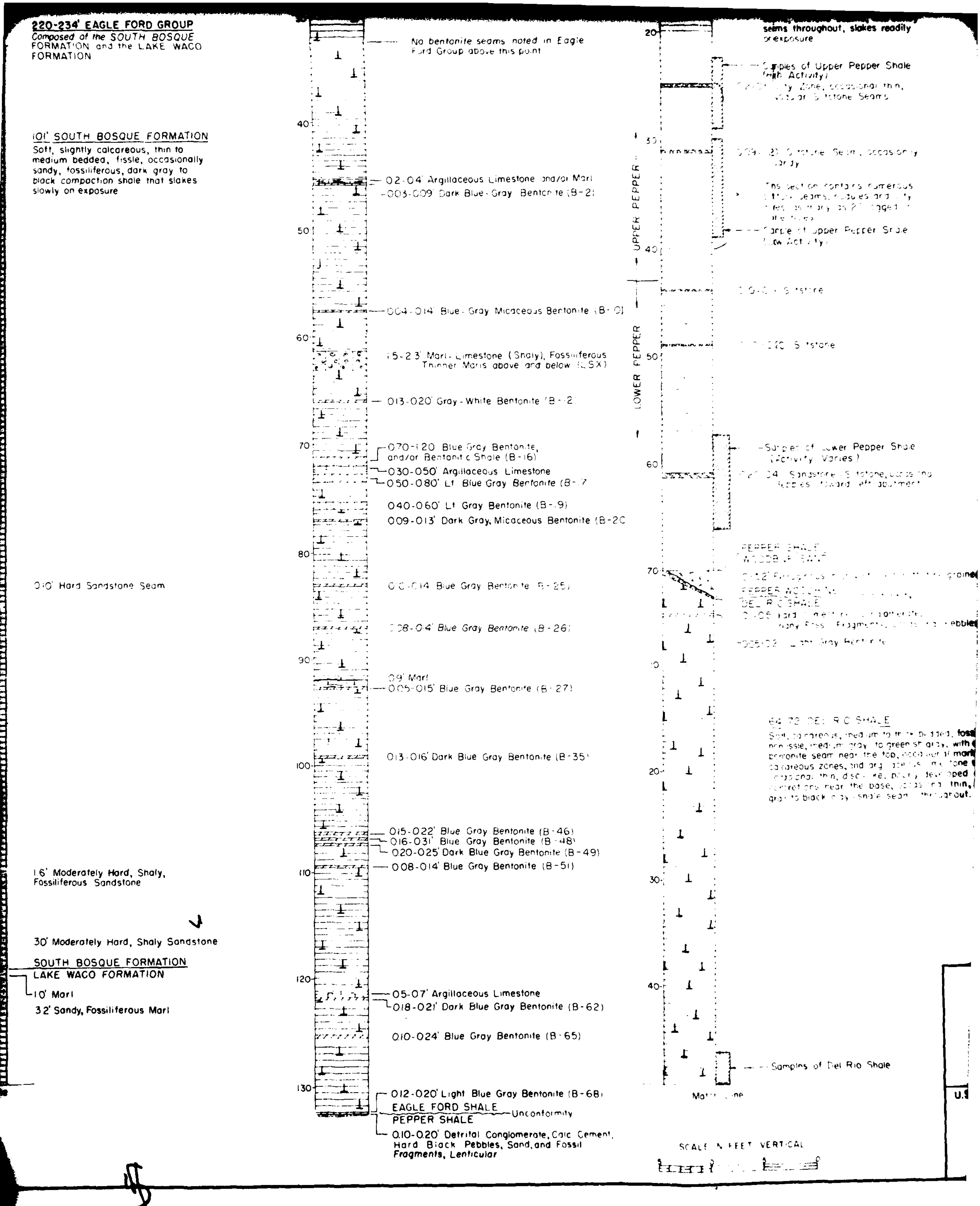


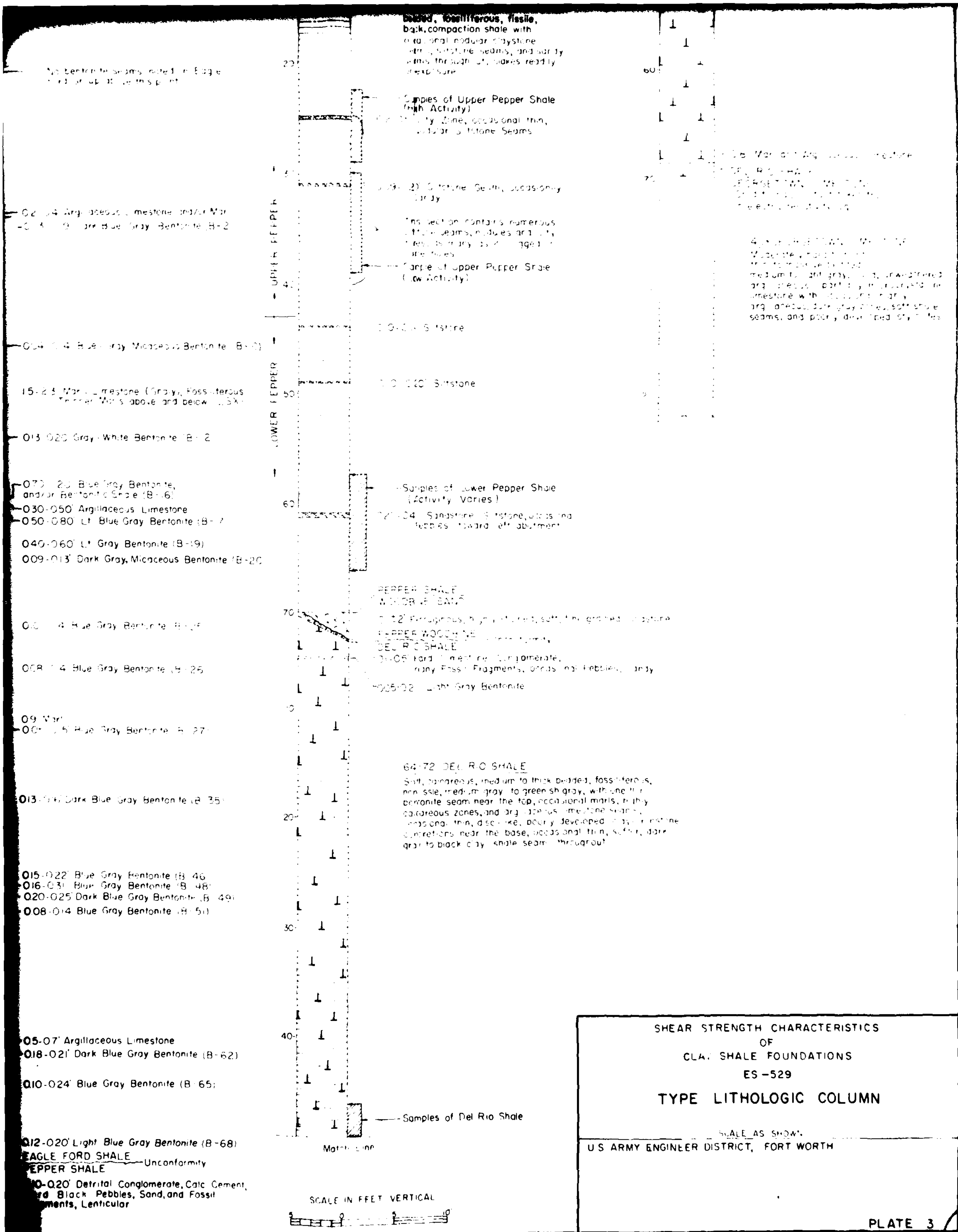
Match Line
IN CHALK
E FORD SHALE
Unconformity
4' Lenticular, Fossiliferous
merate
234' EAGLE FORD GROUP
ed of the SOUTH BOSQUE
ATION and the LAKE WACO
ATION
SOUTH BOSQUE FORMATION
slightly calcareous, thin to
m bedded, fissle, occasionally
, fossiliferous, dark gray to
compaction shale that slakes
on exposure
Hard Sandstone Seam
erately Hard, Shaly,
us Sandstone
133' LAKE WACO FORMATION
Soft to moderately hard, highly calcareous, thin to medium bedded, bentonitic, some softer zones fissle and slake slowly, dark gray to black, highly fossiliferous, occasionally lignitic, with many bentonite seams, marl seams, and argillaceous limestone seams
No bentonite seams noted in Eagle Ford Group above this point
0.2-0.4' Argillaceous Limestone and/or Marl
003-009' Dark Blue-Gray Bentonite (B-2)
004-014' Blue-Gray Micaceous Bentonite (B-10)
1.5-2.3' Marl-Limestone (Shaly), Fossiliferous
Thinner Marls above and below (LSX)
013-020' Gray-White Bentonite (B-12)
070-120' Blue Gray Bentonite, and/or Bentonitic Shale (B-16)
030-050' Argillaceous Limestone
050-080' Lt Blue Gray Bentonite (B-17)
040-060' Lt Gray Bentonite (B-19)
009-013' Dark Gray, Micaceous Bentonite (B-20)
010-014 Blue Gray Bentonite (B-25)
008-014' Blue Gray Bentonite (B-26)
09' Marl
005-015' Blue Gray Bentonite (B-27)
013-016' Dark Blue Gray Bentonite (B-35)
015-022' Blue Gray Bentonite (B-46)
016-031' Blue Gray Bentonite (B-48)
020-025' Dark Blue Gray Bentonite (B-49)
008-014' Blue Gray Bentonite (B-51)
EAGLE FORD SHALE
Unconformity
PEPPER SHALE
0.10-0.20 Detrital Conglomerate, Calc Cement, Hard Black Pebbles, Sand, and Fossil Fragments, Lenticular
04-1.0 Silty Zone with 004-020 Siltstone Seam Included
64-74' PEPPER SHALE
Soft, noncalcareous, thin to medium bedded, fossiliferous, fissle, black, compaction shale with occasional nodular claystone seams, siltstone seams, and sandy seams throughout, slakes readily on exposure
Samples of Upper Pepper Shale (High Activity)
02-0.5 Silty Zone, occasional thin, nodular Siltstone Seams
009-0.20' Siltstone Seam, occasionally sandy
This section contains numerous siltstone seams, nodules and silty zones, as many as 20 logged in core holes
Sample of Upper Pepper Shale (Low Activity)
UPPER PEPPER
LOWER PEPPER
010-014 Siltstone
010-020' Siltstone
Samples of Lower Pepper Shale (Activity Varies)
0.20-0.4' Sandstone, Siltstone, occasional Pebbles toward left abutment
PEPPER SHALE
WOODBINE SAND
0-1.2' Ferruginous, highly stained, soft, fine grained sandstone
PEPPER WOODBINE
DEL RIO SHALE
Unconformity
01-05' Hard Limestone Conglomerate, many Fossil Fragments, occasional Pebbles, sandy
005-020' Light Gray Bentonite
64-72' DEL RIO SHALE
Soft, calcareous, medium to thick bedded, fossiliferous, nonfissle, medium gray to green shgray, with one thin bentonite seam near the top, occasional marls, highly calcareous zones, and argillaceous limestone seams, occasional thin, discrete, poorly developed iron concretions near the base, occasional thin, softer, dark gray to black gray shale seams throughout


EAGLE FORD SHALE
PEPPER SHALE
Unconformity
0.10-0.2' Detrital Conglomerate, Calc Cement, Hard Black Pebbles, Sand, and Fossil Fragments, Lenticular
133' LAKE WACO FORMATION
Soft to moderately hard, highly calcareous, thin to medium bedded, bentonitic, some softer zones fissile and slake slowly, dark gray to black, highly fossiliferous, occasionally lignitic, with many bentonite seams, marl seams, and argillaceous limestone seams
0.4-1.0' Silty Zone with 0.04-0.20' Siltstone Seam included
64-74' PEPPER SHALE
Soft, noncalcareous, thin to medium bedded, fossiliferous, fissile, black, compaction shale with occasional nodular claystone seams, siltstone seams, and sandy seams throughout, slakes readily on exposure
No bentonite seams noted in Eagle Ford Group above this point
Samples of Upper Pepper Shale (High Activity)
0.2-0.5' Silty Zone, occasional thin, nodular Siltstone Seams
0.09-0.2' Siltstone Seam, occasionally sandy
0.2-0.4' Argillaceous Limestone and/or Marl
0.03-0.09' Dark Blue-Gray Bentonite (B-2)
This section contains numerous siltstone seams, nodules and silty zones, as many as 20 logged in some holes
Sample of Upper Pepper Shale (Low Activity)
UPPER PEPPER
LOWER PEPPER
0.10-0.14 Siltstone
0.04-0.14' Blue-Gray Micaceous Bentonite (B-10)
1.5-2.3' Marl-Limestone (Shaly), Fossiliferous Thinner Marls above and below (LSX)
0.10-0.20' Siltstone
0.13-0.20' Gray-White Bentonite (B-12)
0.70-1.20' Blue Gray Bentonite, and/or Bentonitic Shale (B-16)
Samples of Lower Pepper Shale (Activity Varies)
0.30-0.50' Argillaceous Limestone
0.50-0.80' Lt Blue Gray Bentonite (B-17)
0.20-0.40' Sandstone - Siltstone, occasional Pebbles toward left abutment
0.40-0.60' Lt Gray Bentonite (B-19)
0.09-0.13' Dark Gray, Micaceous Bentonite (B-20)
PEPPER SHALE
WOODBINE SAND
0-1.2' Ferruginous, highly stained, soft, fine grained sandstone
0.10-0.14 Blue Gray Bentonite (B-25)
PEPPER WOODBINE
DEL RIO SHALE
Unconformity
0.1-0.5' Hard Limestone - Conglomerate, many Fossil Fragments, occasional Pebbles, Sandy
0.08-0.14 Blue Gray Bentonite (B-26)
0.05-0.20' Light Gray Bentonite
0.9' Marl
0.05-0.15' Blue Gray Bentonite (B-27)
64-72' DEL RIO SHALE
Soft, calcareous, medium to thick bedded, fossiliferous, nonfissile, medium gray to greenish gray, with one thin bentonite seam near the top, occasional marls, highly calcareous zones, and argillaceous limestone seams, occasional thin, disc-like, poorly developed clay ironstone concretions near the base, occasional thin, softer, dark gray to black clay-shale seams throughout
0.13-0.16' Dark Blue Gray Bentonite (B-35)
0.15-0.22' Blue Gray Bentonite (B-46)
0.16-0.31' Blue Gray Bentonite (B-48)
0.20-0.25' Dark Blue Gray Bentonite (B-49)
0.08-0.14' Blue Gray Bentonite (B-51)
Match Line
1.4-2.3' Highly Calcareous Shale and Marl
1.7-2.2' Highly Calcareous Shale and Marl
0.8 Marl and Argillaceous Limestone
DEL RIO SHALE
GEORGETOWN LIMESTONE
40± GEORGETOWN LIMESTONE
seams, and poorly developed stylolites
0
10
20
30
40
50
60
70



Upper Cretaceous
Gulf Series
Austin Group
Austin Chalk
Unconformity
Eagle Ford Group
South Bosque Shale
Lake Waco Shale
Unconformity
Woodbine Group
Pepper Shale
Thin Woodbine Facies
Unconformity
Lower Cretaceous
Comanche Series
Washita Group
Georgetown LS
Del Rio Shale
Possible Buda LS Remnant
140
150
160
170
180
190
200
210
220
230
100'+ AUSTIN CHALK
Moderately hard, argillaceous, medium to massive bedded, tan-gray to brown to gray, highly fossiliferous marl-chalk with occasional shale and bentonite seams. Top 138' removed by erosion
070-090' Light Gray Bentonite
010-015' Light Gray Bentonite
AUSTIN CHALK
Unconformity
EAGLE FORD SHALE
00-04' Lenticular Fossiliferous Conglomerate
10
20
30
40
50
60
70
80
90
100
0
10
Match Line
220-234' EA
Composed of th
FORMATION a
FORMATION
0' SOUTH B
Soft, slightly c
medium bedded
sandy, fossilifer
black compactio
slowly on expos
Hard Sands
6' Moderately H
Fossiliferous Sand
30' Moderately H
SOUTH BOSQU
LAKE WACO FO
0' Marl
3.2' Sandy, Fossili


220-234' EAGLE FORD GROUP
Composed of the SOUTH BOSQUE FORMATION and the LAKE WACO FORMATION
101' SOUTH BOSQUE FORMATION
Soft, slightly calcareous, thin to medium bedded, fissile, occasionally sandy, fossiliferous, dark gray to black compaction shale that slakes slowly on exposure
0.10' Hard Sandstone Seam
1.6' Moderately Hard, Shaly, Fossiliferous Sandstone
3.0' Moderately Hard, Shaly Sandstone
SOUTH BOSQUE FORMATION
LAKE WACO FORMATION
1.0' Marl
3.2' Sandy, Fossiliferous Marl
No bentonite seams noted in Eagle Ford Group above this point
0.2-0.4' Argillaceous Limestone and/or Marl
0.03-0.09' Dark Blue-Gray Bentonite (B-2)
0.04-0.14' Blue-Gray Micaceous Bentonite (B-10)
1.5-2.3' Marl-Limestone (Shaly), Fossiliferous Thinner Marls above and below (LSX)
0.13-0.20' Gray-White Bentonite (B-12)
0.70-1.20' Blue Gray Bentonite, and/or Bentonitic Shale (B-16)
0.30-0.50' Argillaceous Limestone
0.50-0.80' Lt Blue Gray Bentonite (B-17)
0.40-0.60' Lt Gray Bentonite (B-19)
0.09-0.13' Dark Gray, Micaceous Bentonite (B-20)
0.10-0.14' Blue Gray Bentonite (B-25)
0.08-0.14' Blue Gray Bentonite (B-26)
0.9' Marl
0.05-0.15' Blue Gray Bentonite (B-27)
0.13-0.16' Dark Blue Gray Bentonite (B-35)
0.15-0.22' Blue Gray Bentonite (B-46)
0.16-0.31' Blue Gray Bentonite (B-48)
0.20-0.25' Dark Blue Gray Bentonite (B-49)
0.08-0.14' Blue Gray Bentonite (B-51)
0.5-0.7' Argillaceous Limestone
0.18-0.21' Dark Blue Gray Bentonite (B-62)
0.10-0.24' Blue Gray Bentonite (B-65)
0.12-0.20' Light Blue Gray Bentonite (B-68)
EAGLE FORD SHALE
PEPPER SHALE
Unconformity
0.10-0.20' Detrital Conglomerate, Calc Cement, Hard Black Pebbles, Sand, and Fossil Fragments, Lenticular
seams throughout, slakes readily on exposure
Samples of Upper Pepper Shale (High Activity)
Samples of Upper Pepper Shale (Low Activity)
UPPER PEPPER
LOWER PEPPER
Samples of Lower Pepper Shale (Activity Varies)
PEPPER SHALE
WOODBINE SAND
PEPPER WOODBINE
DEL RIO SHALE
64.72' DEL RIO SHALE
Samples of Del Rio Shale
SCALE IN FEET VERTICAL



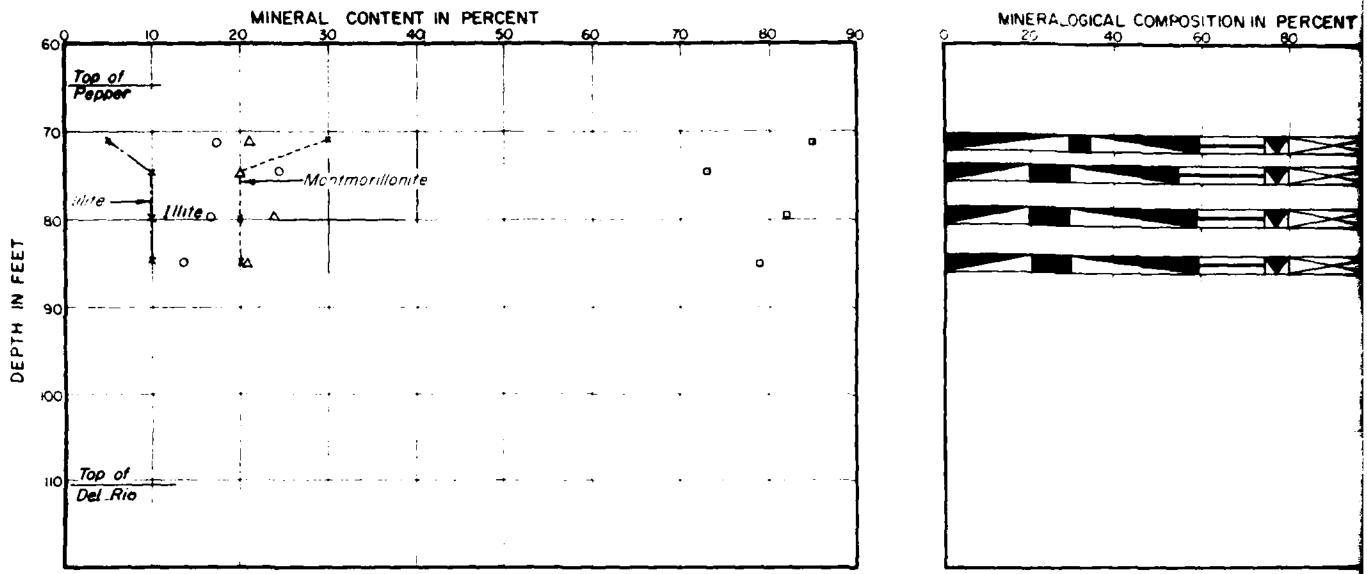
SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529

TYPE LITHOLOGIC COLUMN

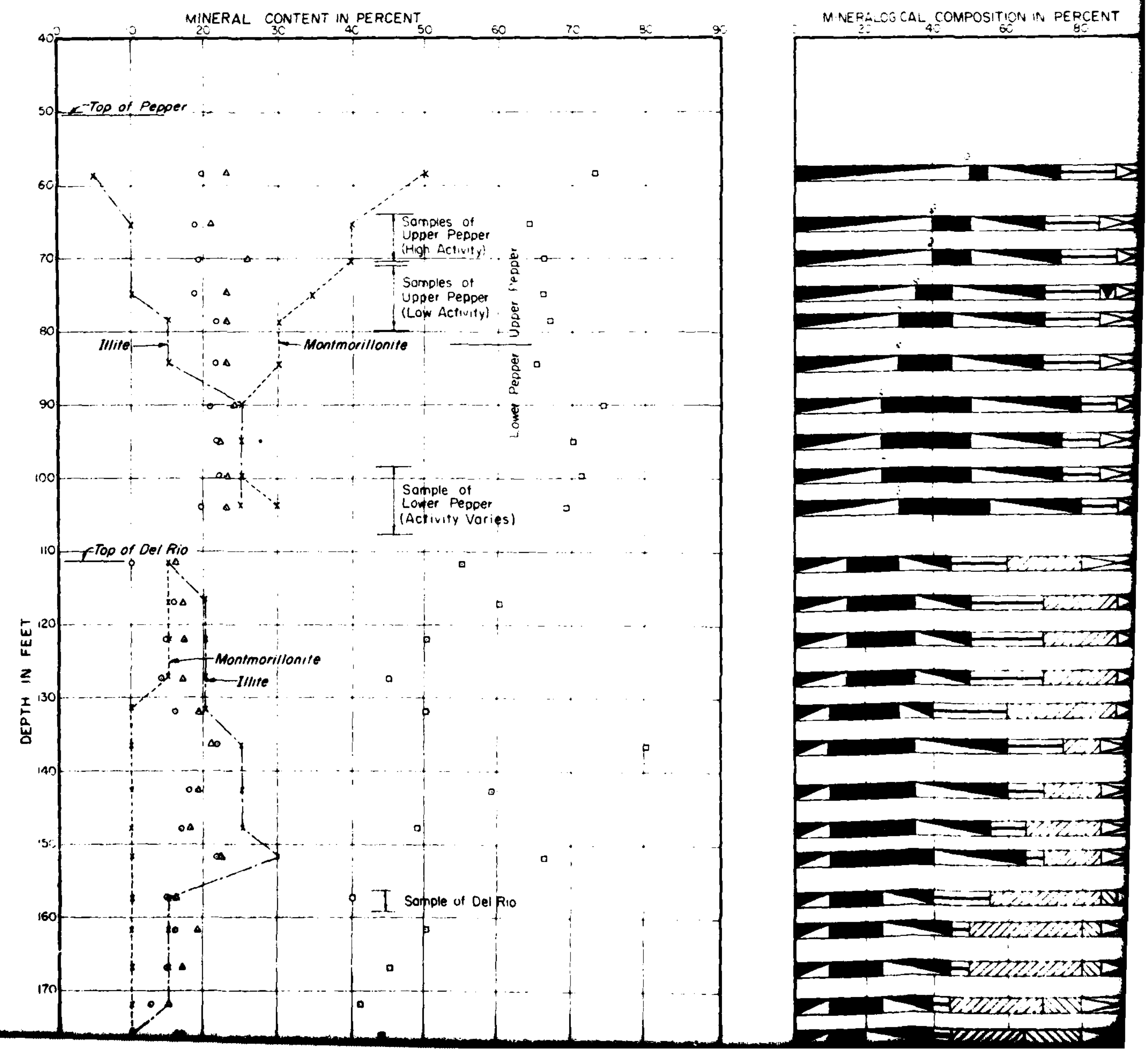
SCALE AS SHOWN

U S ARMY ENGINEER DISTRICT, FORT WORTH

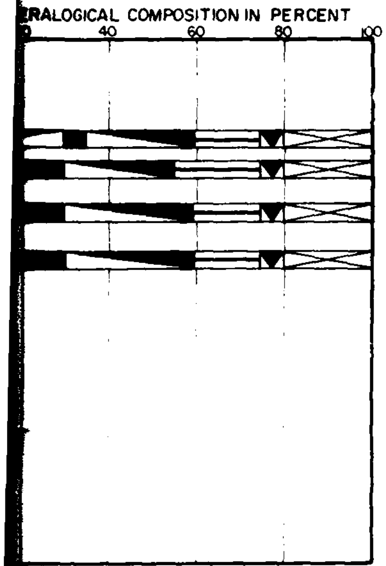
PLATE 3

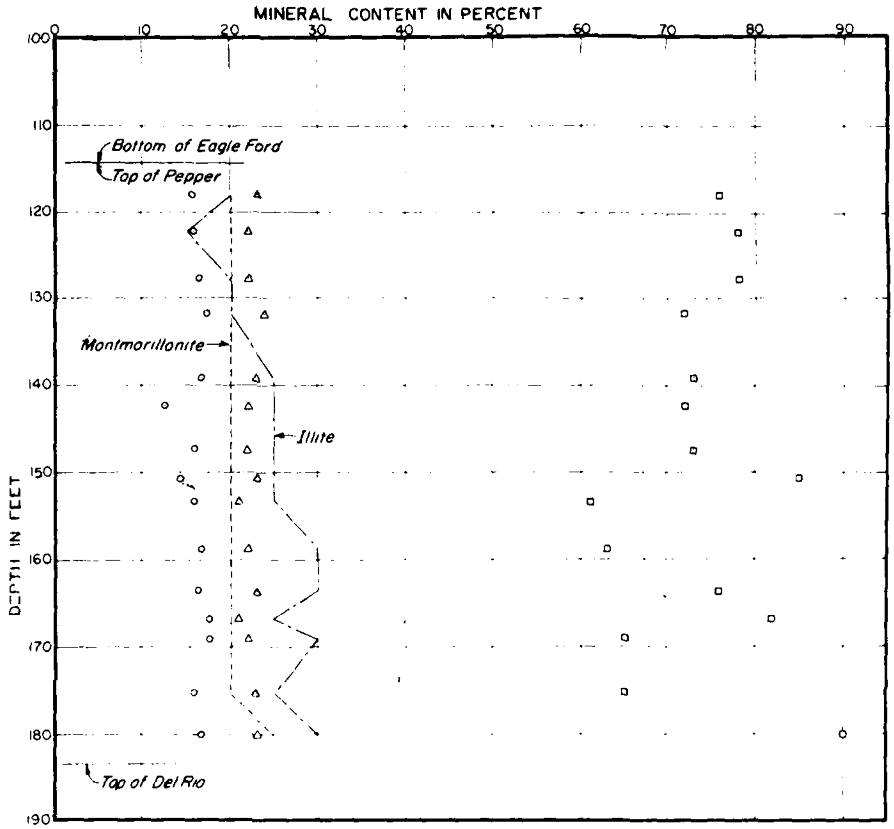


BORING 8A6C-354
STA 55+00, 55' Rt
Top El 453.3

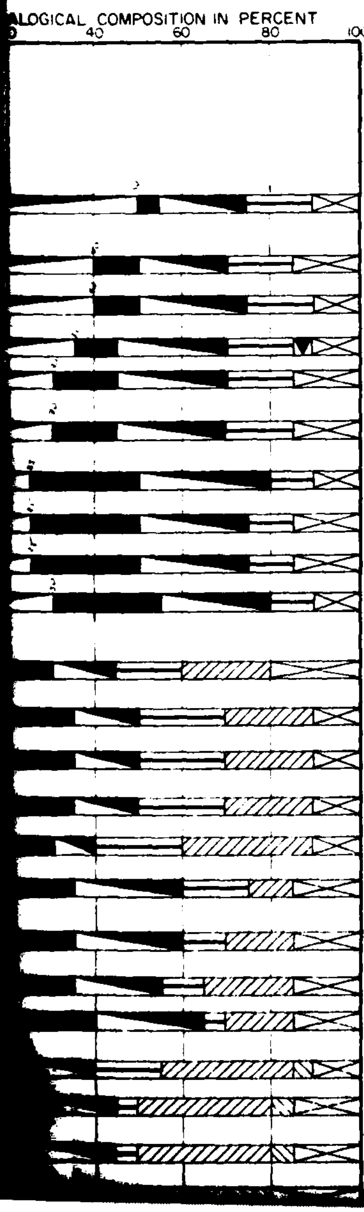


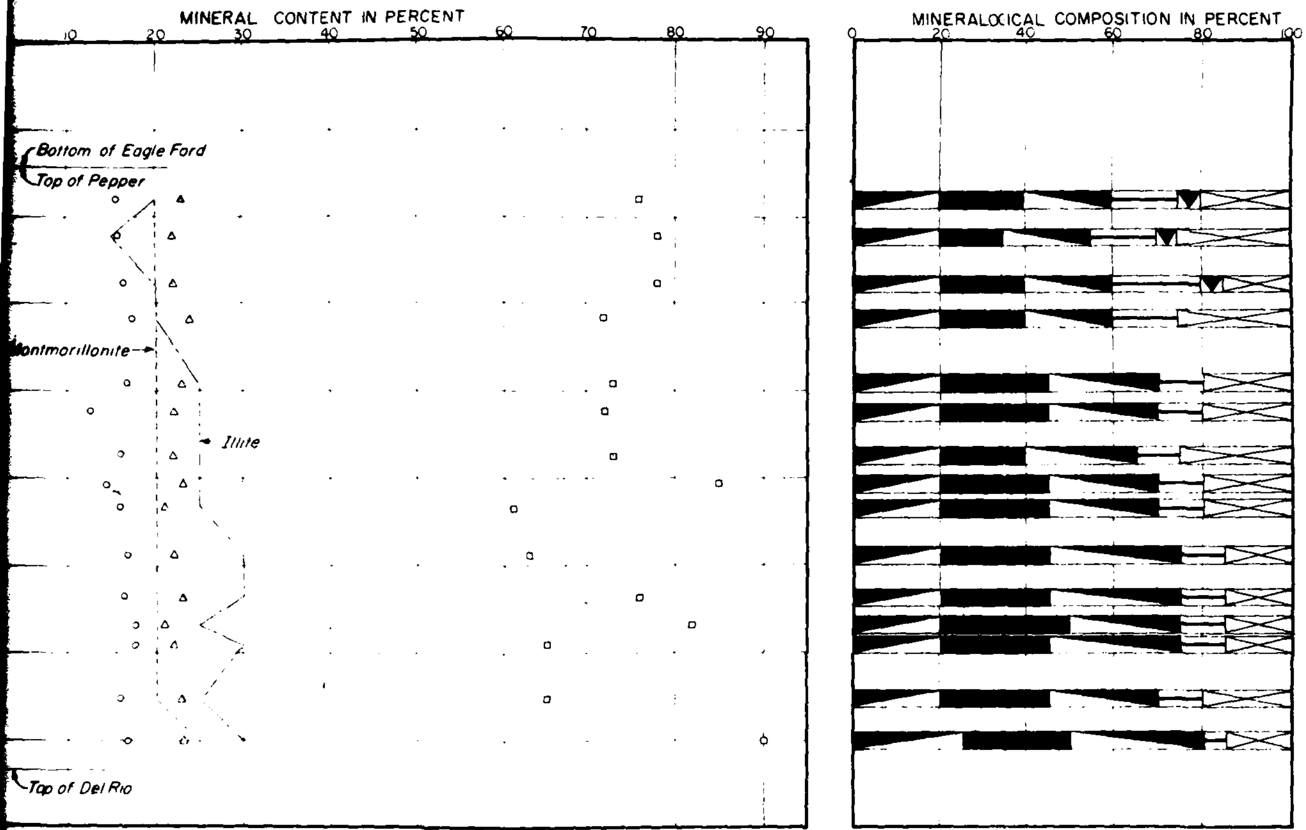
12



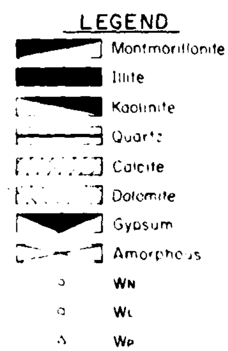


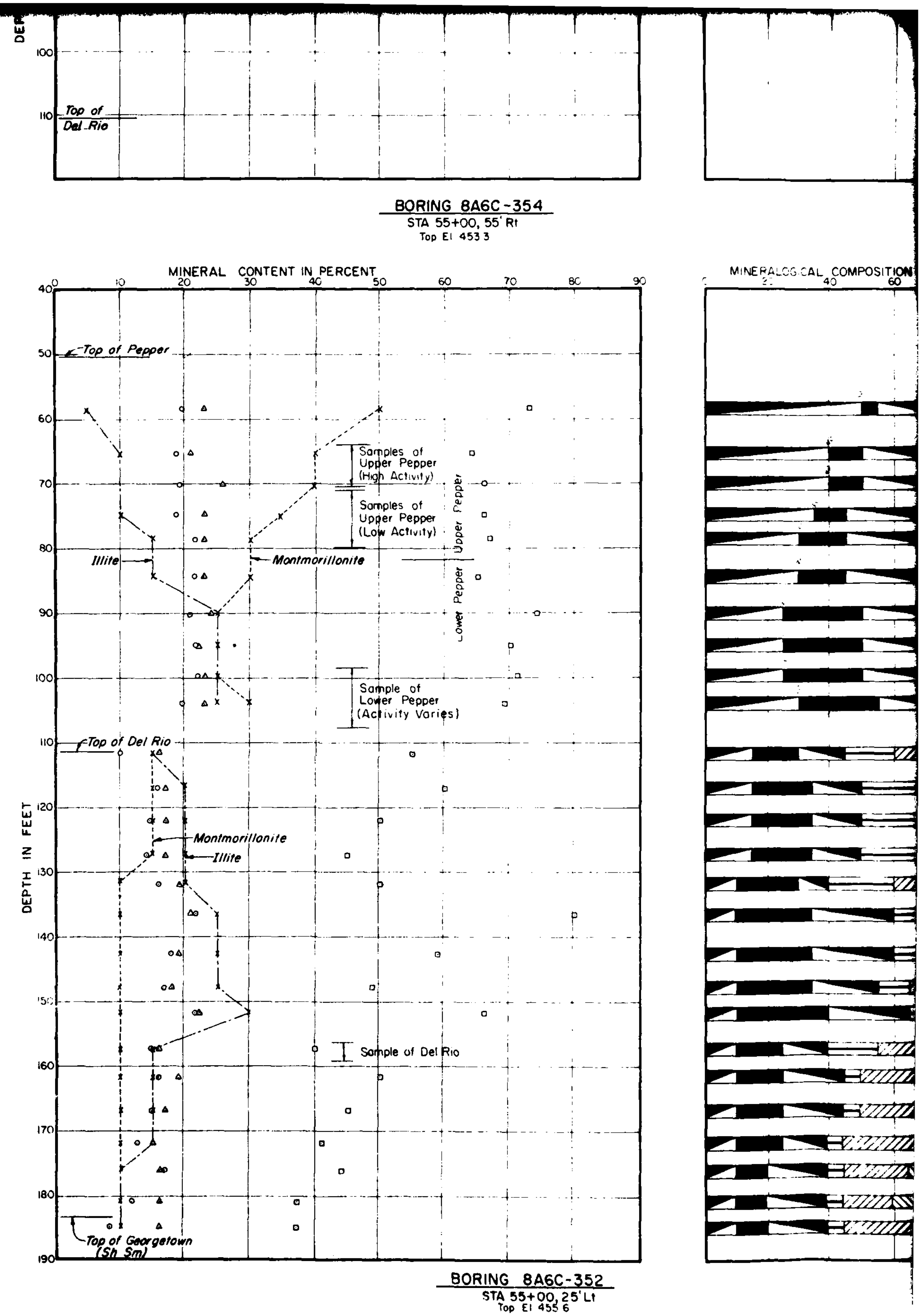
BORING 6C-167
STA 31+00, ℄
Top E 409.0



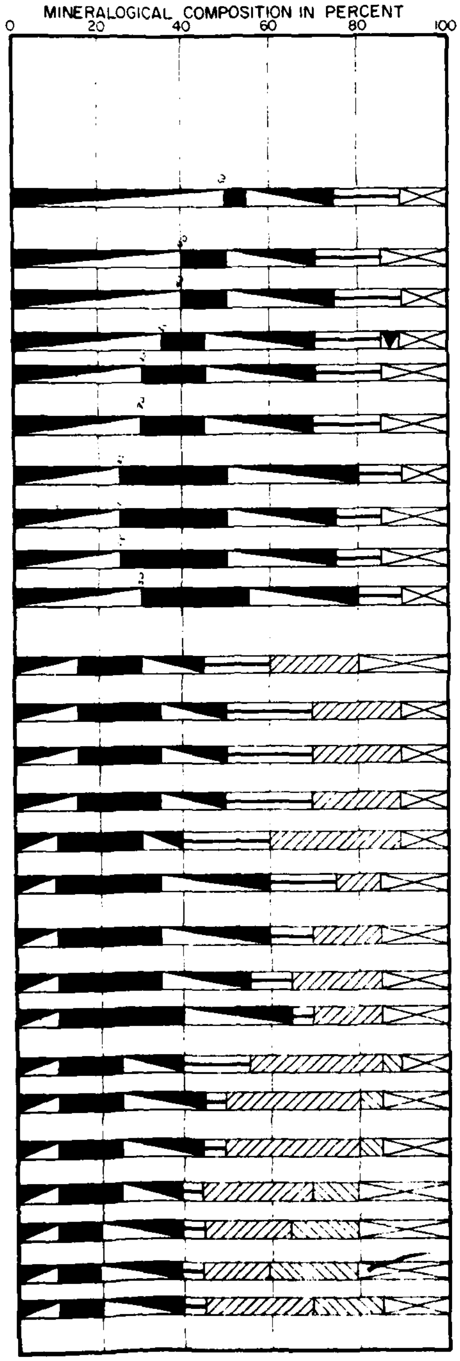


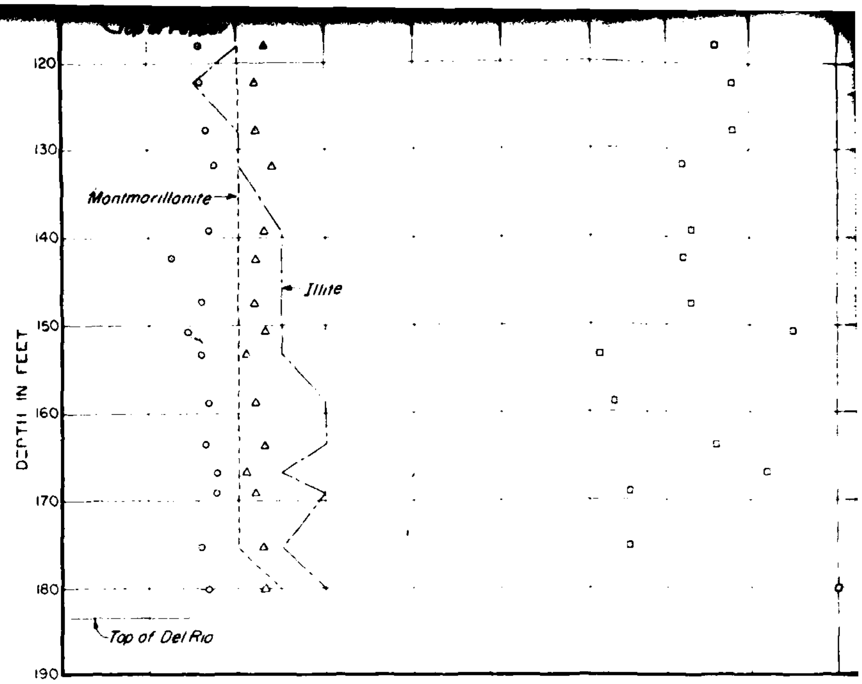
BORING 6C-167
STA 31+00, ℄
Top El 409.0



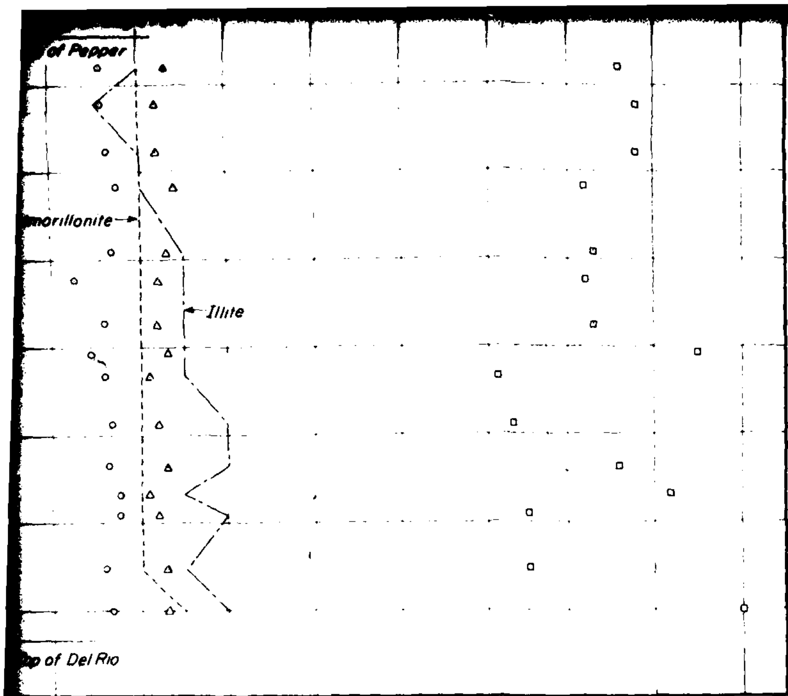


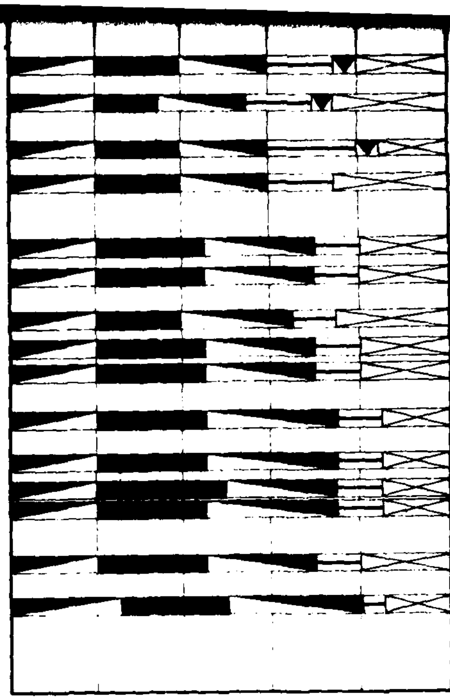
Top of Del Rio
BORING 8A6C-354
STA 55+00, 55' Rt
Top El 453 3
MINERAL CONTENT IN PERCENT
DEPTH IN FEET
Top of Pepper
Samples of Upper Pepper (High Activity)
Samples of Upper Pepper (Low Activity)
Upper Pepper
Lower Pepper
Illite
Montmorillonite
Sample of Lower Pepper (Activity Varies)
Top of Del Rio
Montmorillonite
Illite
Sample of Del Rio
Top of Georgetown (Sh Sm)
MINERALOGICAL COMPOSITION
BORING 8A6C-352
STA 55+00, 25' Lt
Top El 455 6



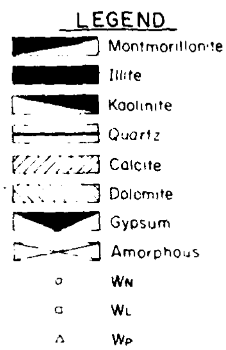


BORING 6C-167
STA 31+00, ℄





BORING 6C-167
STA 31+00, ℄
Top El. 409.0



SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES - 529

MINERALOGICAL COMPOSITION

SCALE AS SHOWN

U.S. ARMY ENGINEER DISTRICT, FORT WORTH

PLATE 4

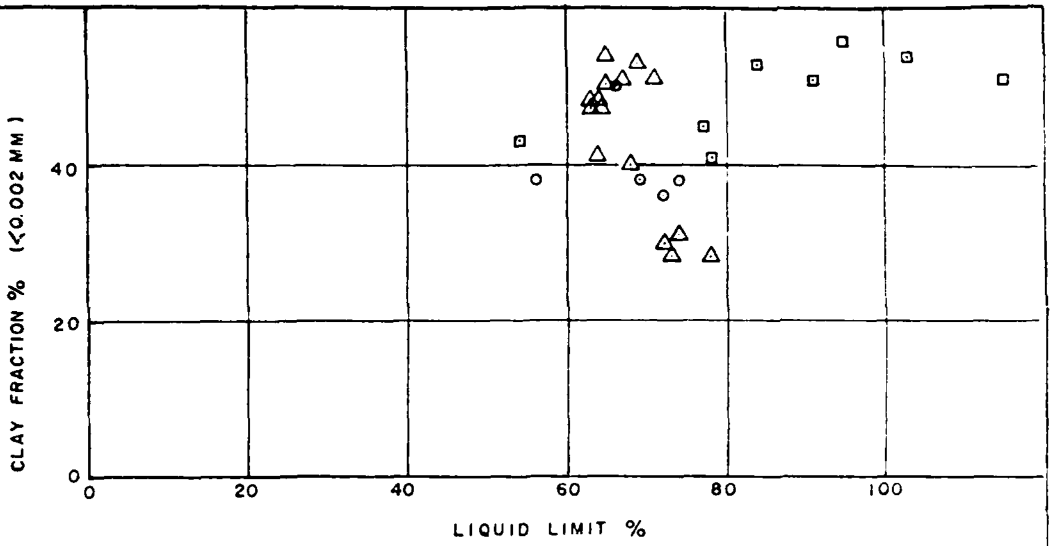


FIGURE 1

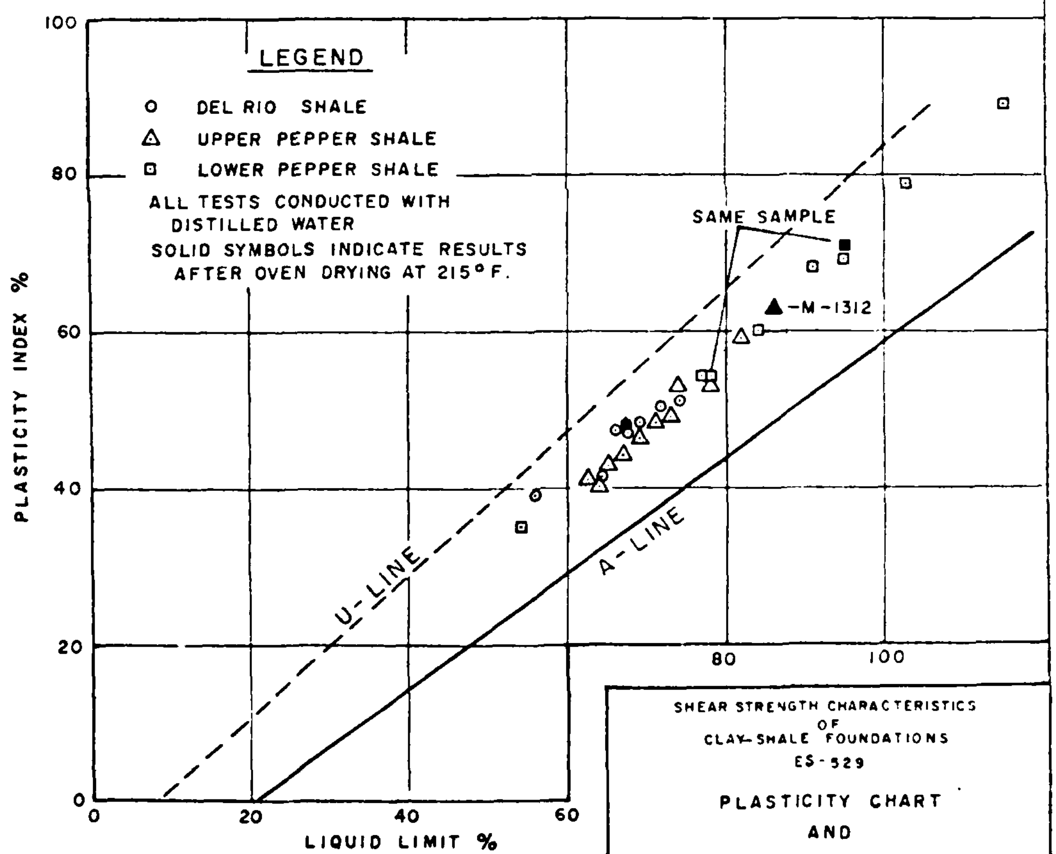


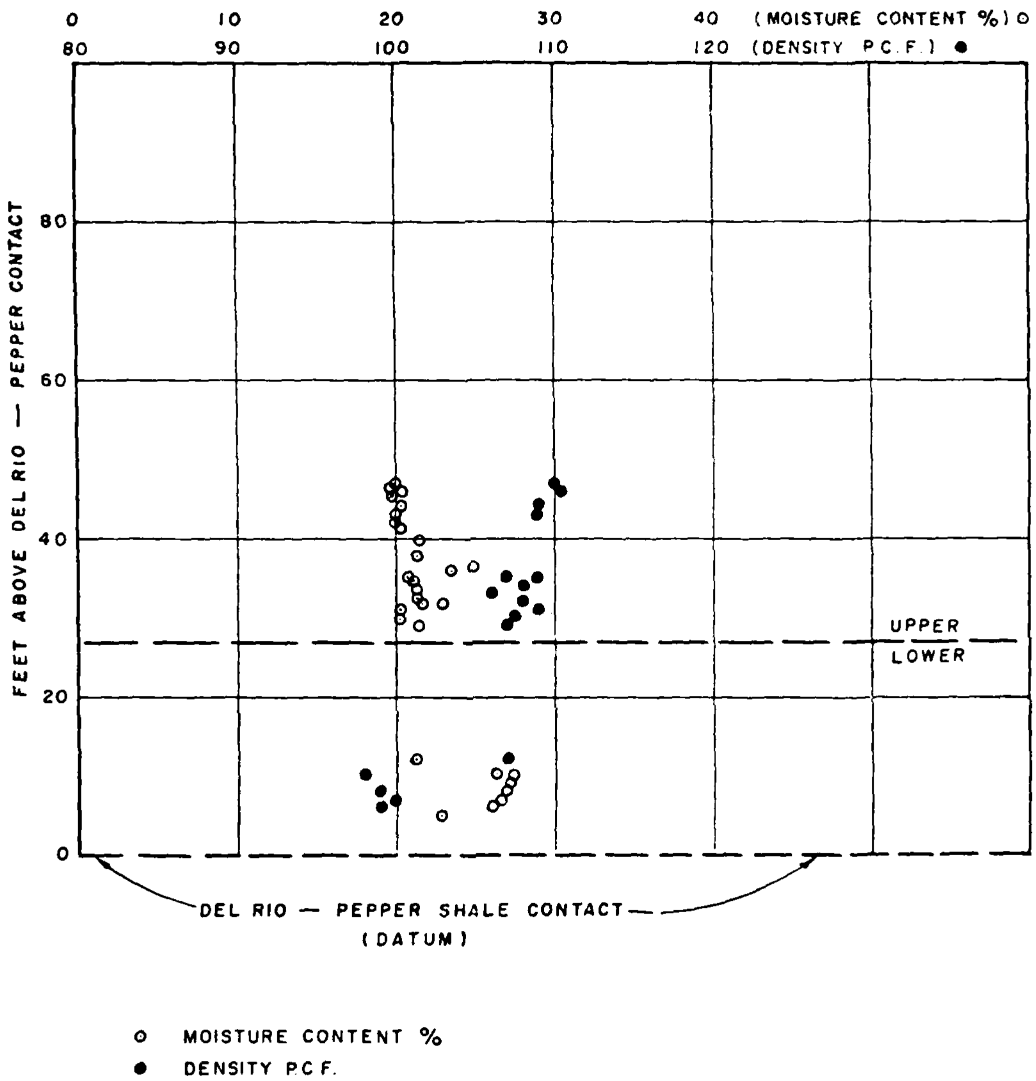
FIGURE 2

SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

PLASTICITY CHART
AND
PERCENT COLLOIDS

U S ARMY ENGINEER DISTRICT, FT WORTH 1958

PLATE 5

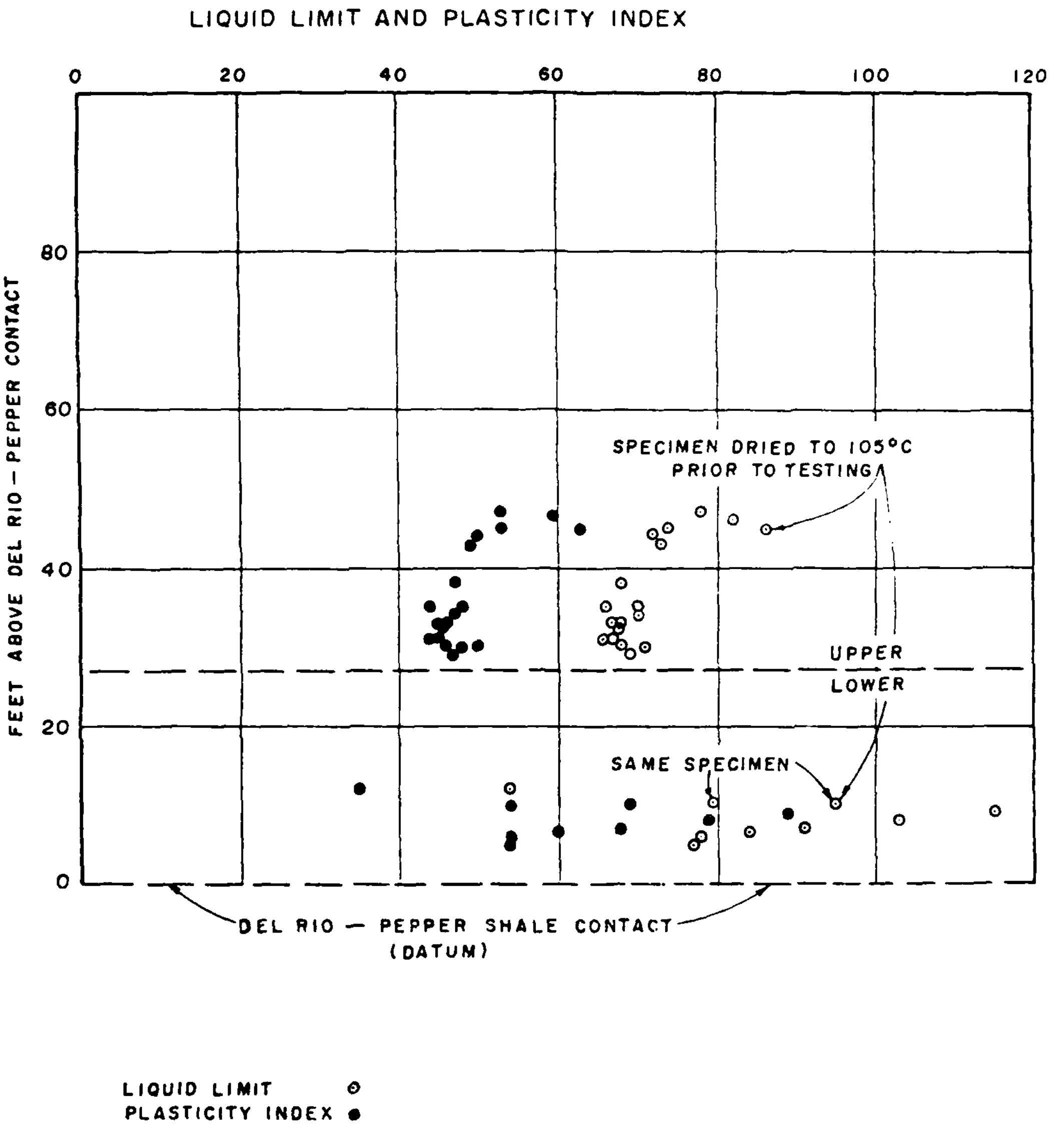


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

PEPPER SHALE
MOISTURE CONTENT AND DENSITY

U.S. ARMY ENGINEER DISTRICT, FT WORTH 1968

PLATE 6

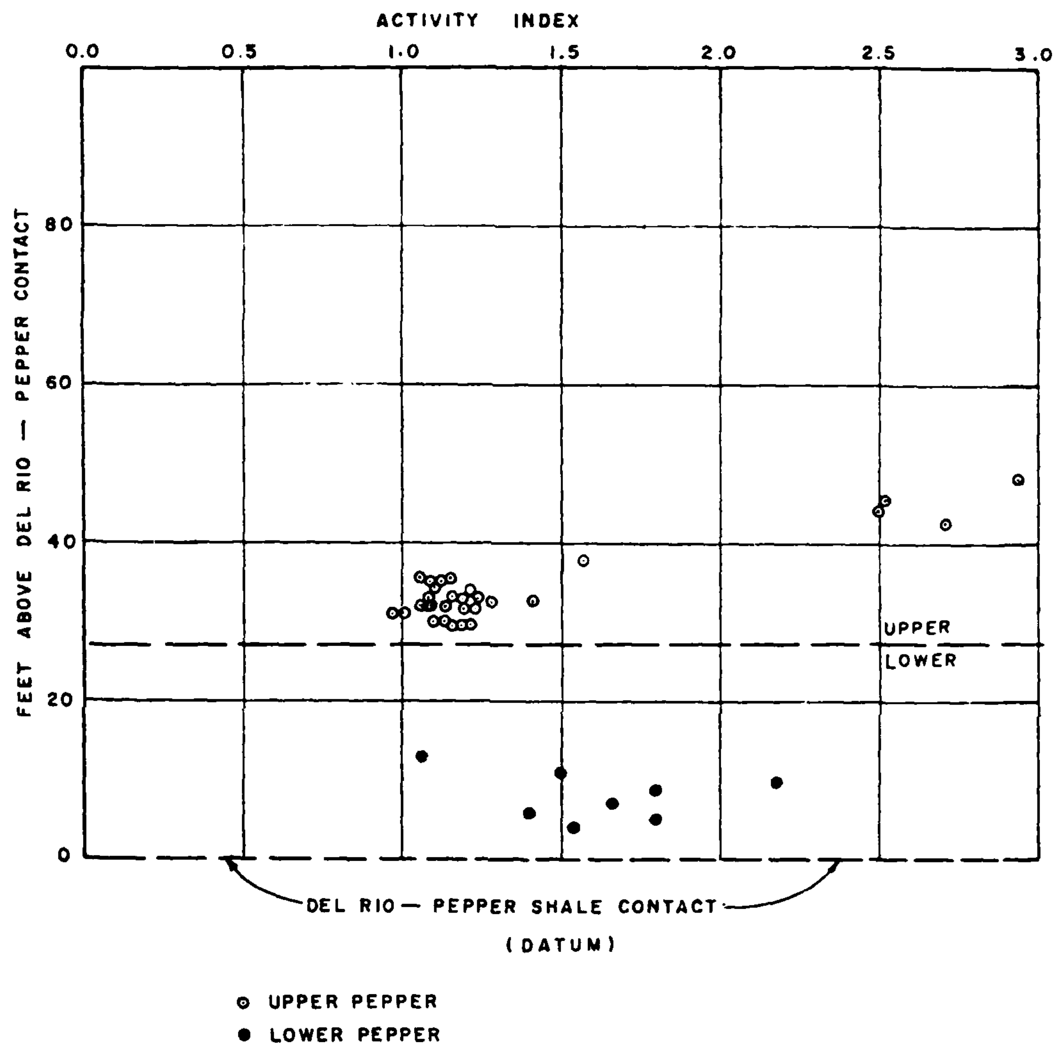


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

PEPPER SHALE
SOIL INDICES

U S ARMY ENGINEER DISTRICT, FT WORTH 1968

PLATE 7

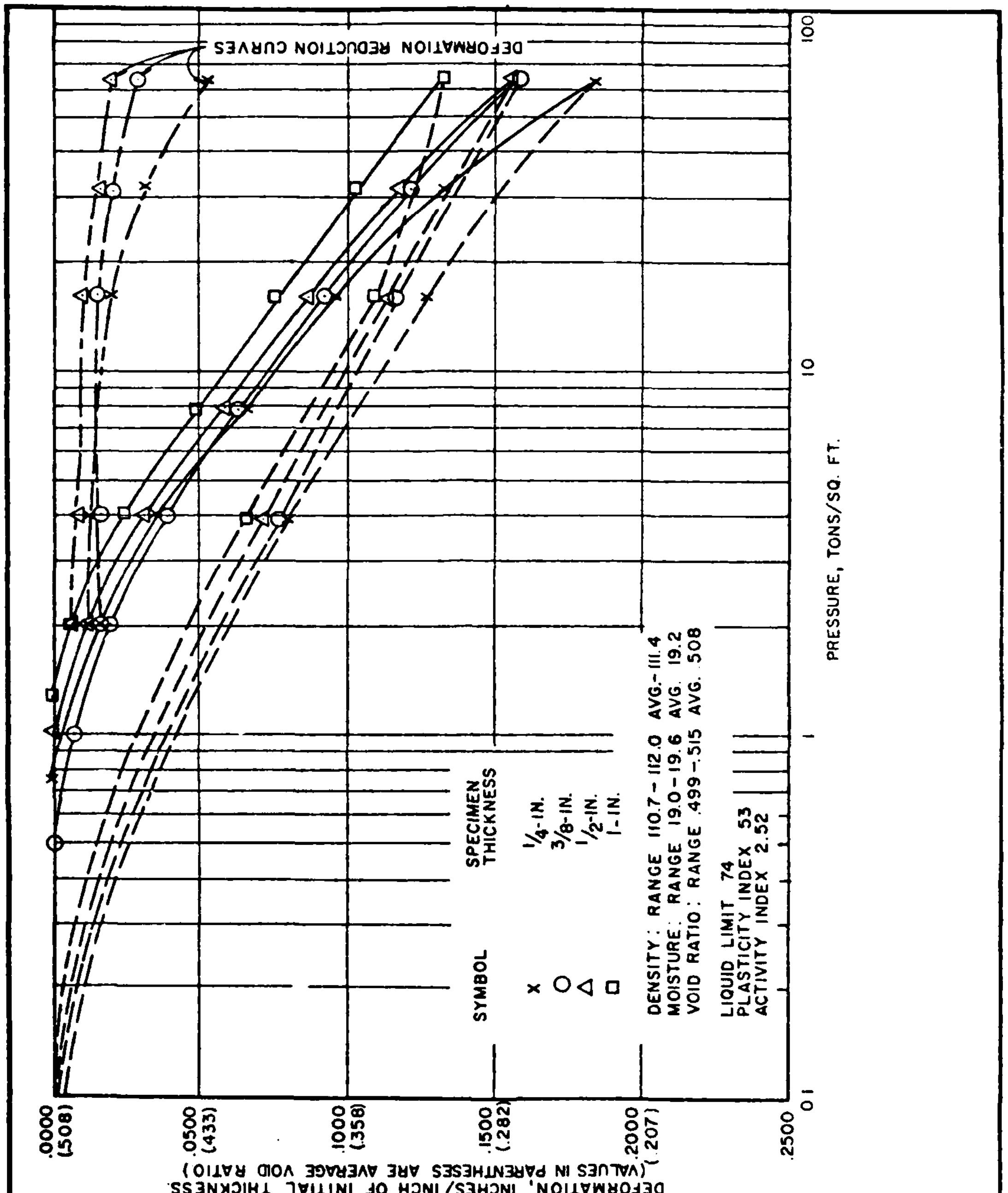


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

PEPPER SHALE
ACTIVITY INDEX

U.S. ARMY ENGINEER DISTRICT, FT WORTH 1968

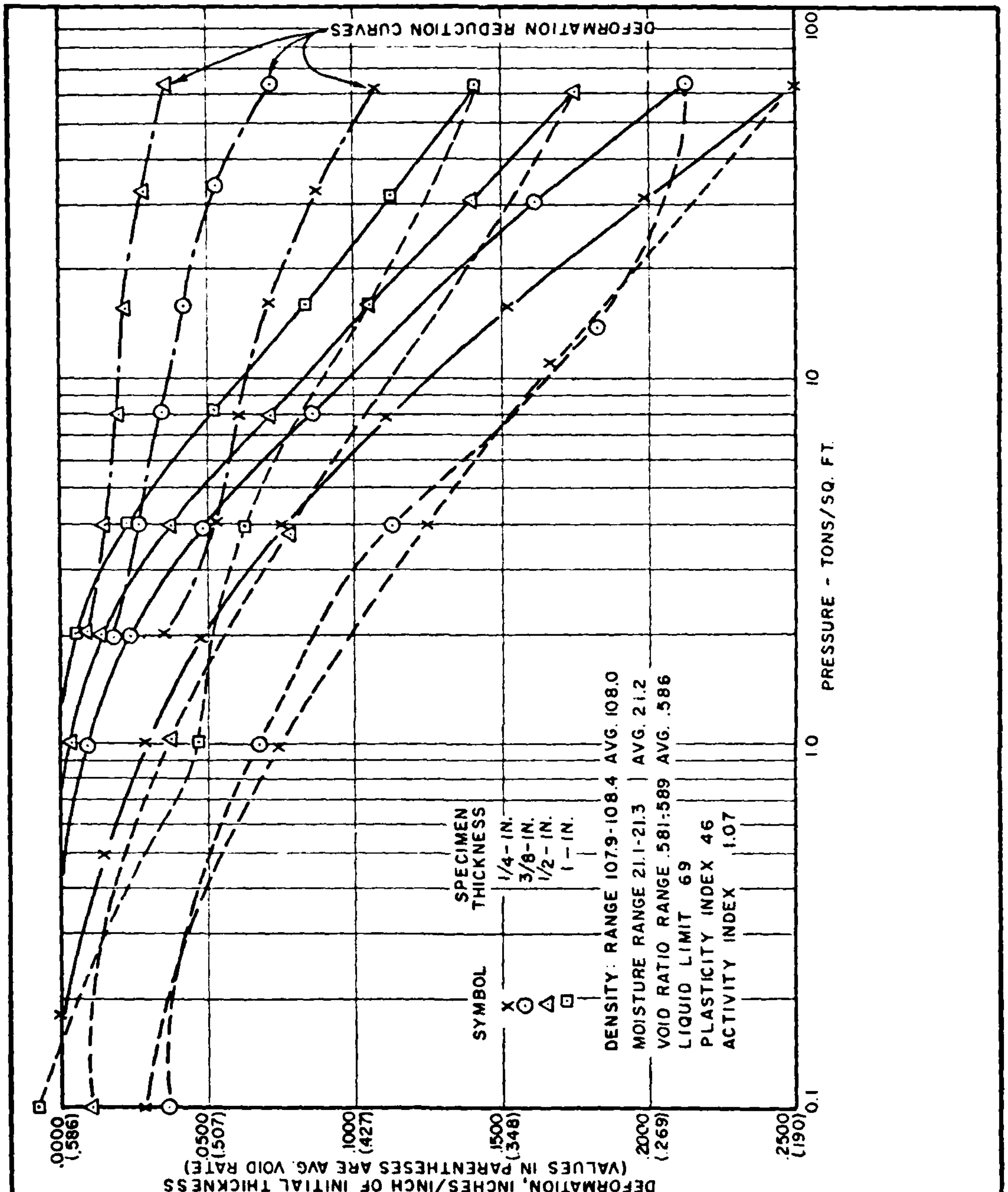
PLATE 8



SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529

CONSOLIDATION TESTS
UPPER PEPPER SHALE
BORING 8A6C-445
DEPTH 51 8 - 52 7

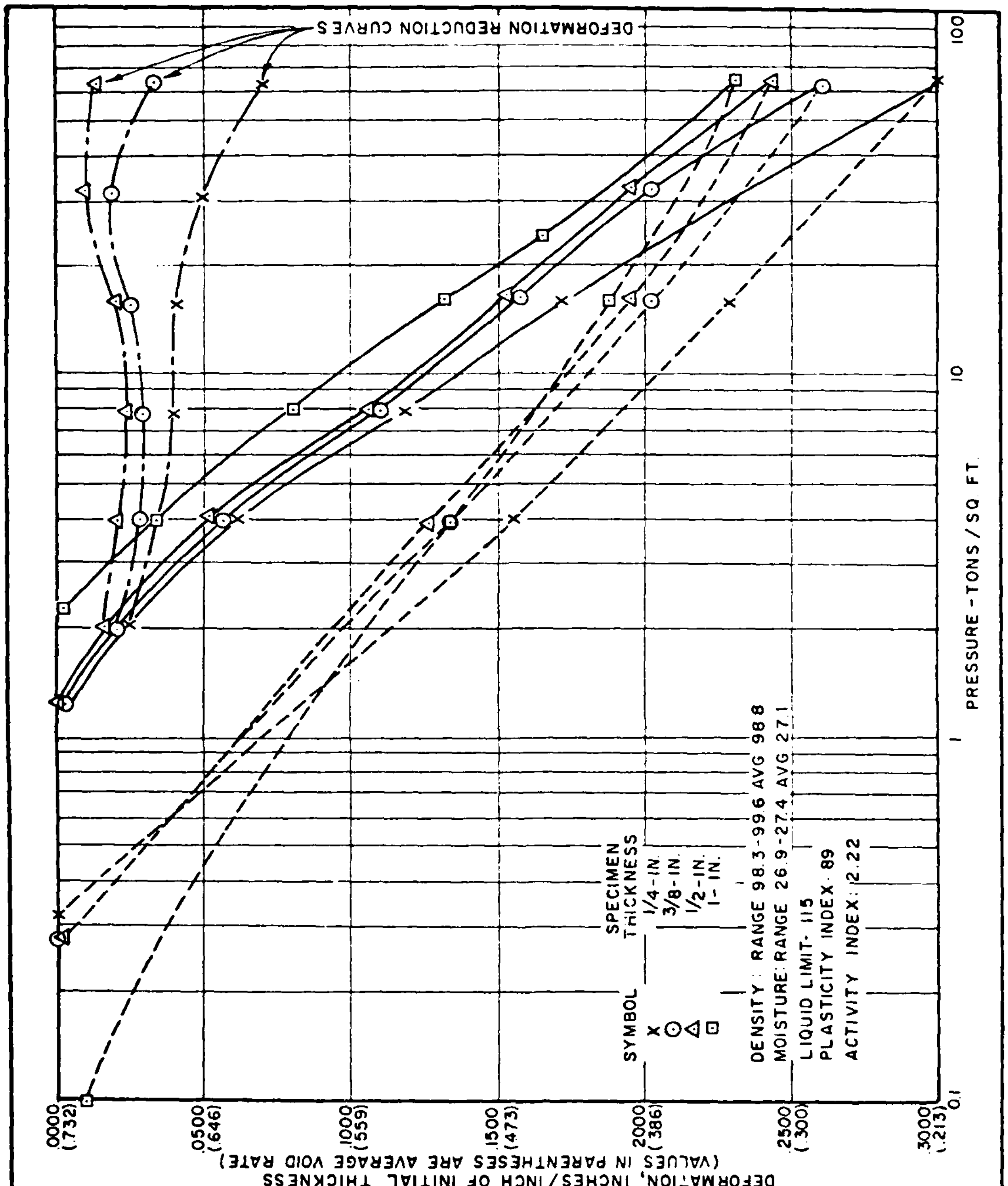
U.S. ARMY ENGINEER DISTRICT, FT. WORTH — JAN. 1968



SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529
CONSOLIDATION TESTS
UPPER PEPPER SHALE
BORING 8A6C-446
DEPTH 32.4-33.4

U.S. ARMY ENGINEER DISTRICT, FT WORTH JAN 1968

PLATE 10



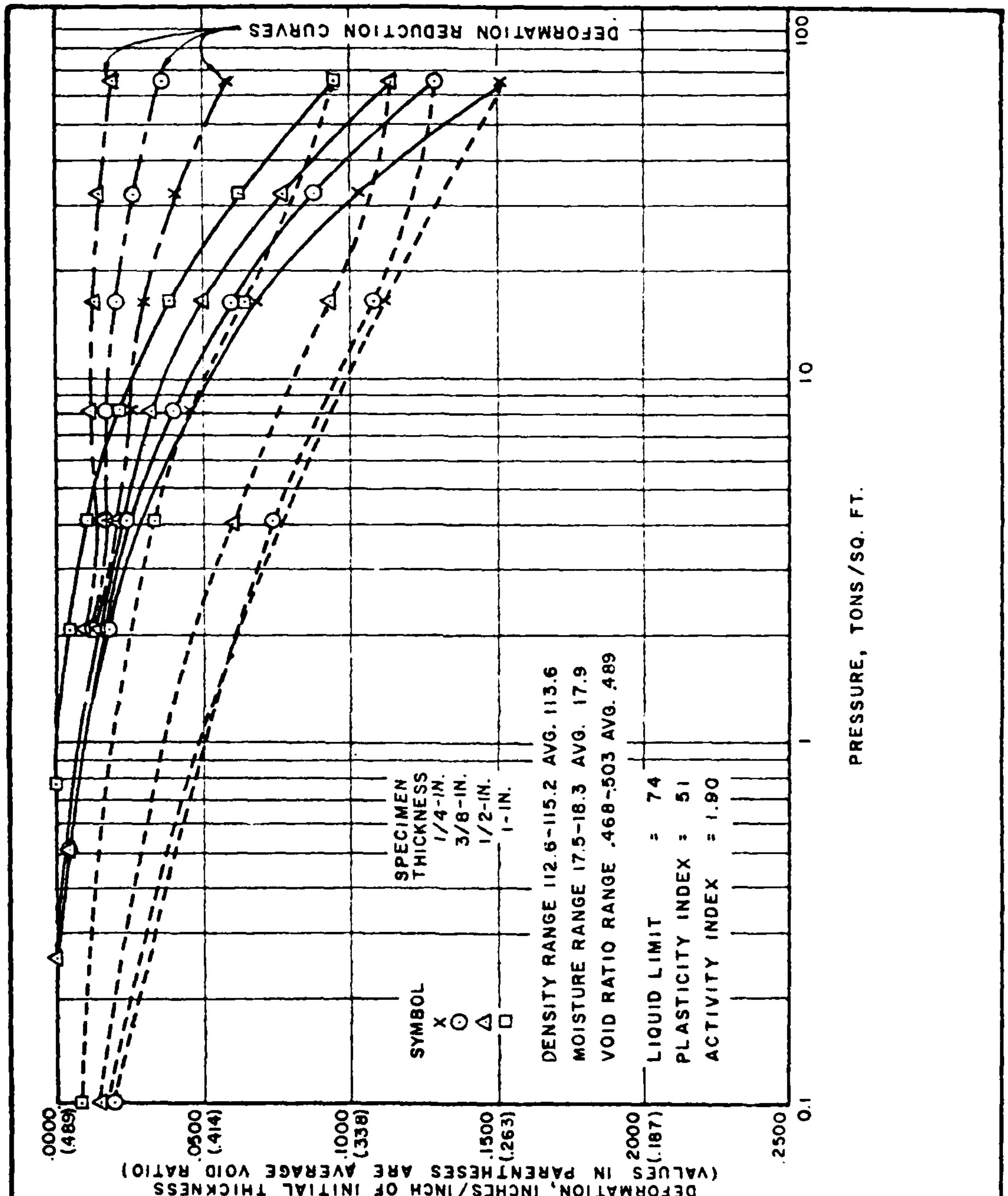
SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS

ES-529

CONSOLIDATION TESTS
LOWER PEPPER SHALE
BORING 8A6C - 445
DEPTH 87.3-88.2

U.S. ARMY ENGINEER DISTRICT, FT. WORTH JAN 1968

PLATE 11



SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES - 529

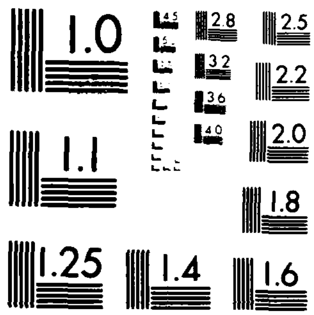
CONSOLIDATION TESTS
DEL RIO SHALE
BORING DR- 4
DEPTH 11.8 - 12.7

U.S ARMY ENGINEER DISTRICT, FT. WORTH JAN. 1968

PLATE 12

AD-A143 018 ENGINEERING PROPERTIES OF CLAY SHALES REPORT 5 STRENGTH 2/2
AND DEFORMATION P..(U) ARMY ENGINEER WATERWAYS
EXPERIMENT STATION VICKSBURG MS W R STROMAN ET AL.
UNCLASSIFIED APR 84 WES/TR/S-71-6-5 F/G 8/13 NL

END
DATE
FILMED
9-84
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS 1963 A

APPENDIX B: NOTATION

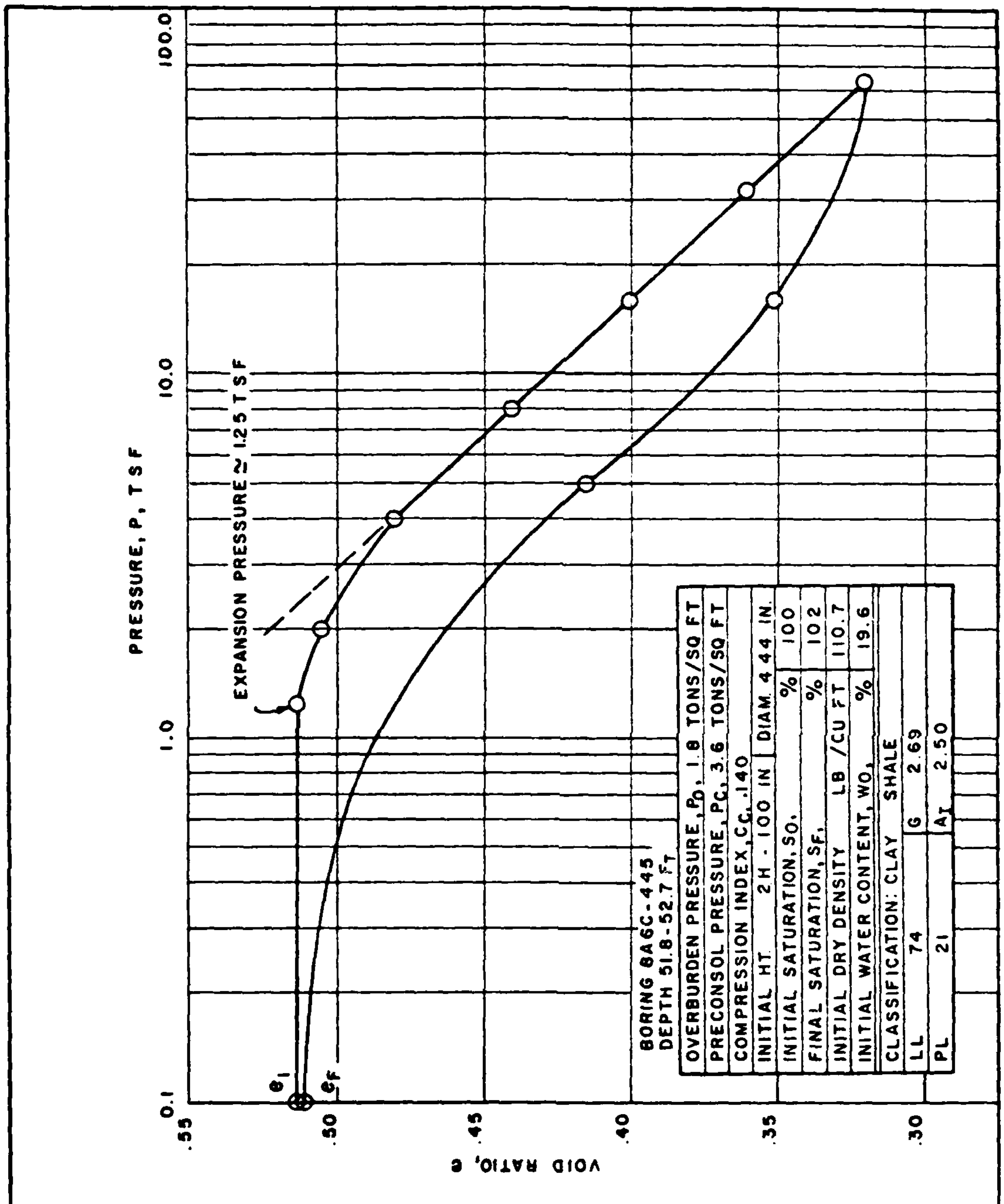
A	Cross-sectional area of test specimen
A_I	Activity index (plasticity index/percent-0.002 mm - 10)
C_c	Compression index
C_α	Coefficient of secondary compression
e	Void ratio
e_o	Initial void ratio
G_s	Specific gravity of soil solids
H	Height of test specimen
LL	Liquid limit
LS	Linear shrinkage
N	Number of blows of liquid limit cup
p	Pressure
P	Shear force
PI	Plasticity index
PL	Plastic limit
Q_n	Unconsolidated, undrained triaxial, constant strain
Q_{ss}	Unconsolidated, undrained triaxial, stress control
s	Shear stress
s_{ff}	Shear stress on the failure plane at failure
S_f	Final saturation
S_i, S_o	Initial saturation
t	Time
t_c	Time subjected to all-around stress prior to applying deviato stress
t_f	Time to failure after first application of shear stress
t_{50}	Time at 50 percent primary consolidation
u	Pore pressure
w_f	Final water content
w_i, w_o	Initial water content
w_N	Water content at N blows of cup
γ_d, γ_i	Initial dry density, pcf
θ	Angle between major principal plane and failure plane
σ	Normal stress, tsf
σ_1	Major principal stress

σ_3	Minor principal stress
$\bar{\sigma}_1$	Effective major principal stress
$\bar{\sigma}_3$	Effective minor principal stress
σ_{ch}	Chamber pressure, tsf
$\sigma_1 - \sigma_3$	Deviator stress
$\bar{\sigma}_1/\bar{\sigma}_3$	Principal stress ratio
τ, τ_{max}	Maximum shear strength, tsf

APPENDIX A

LABORATORY TEST DATA*

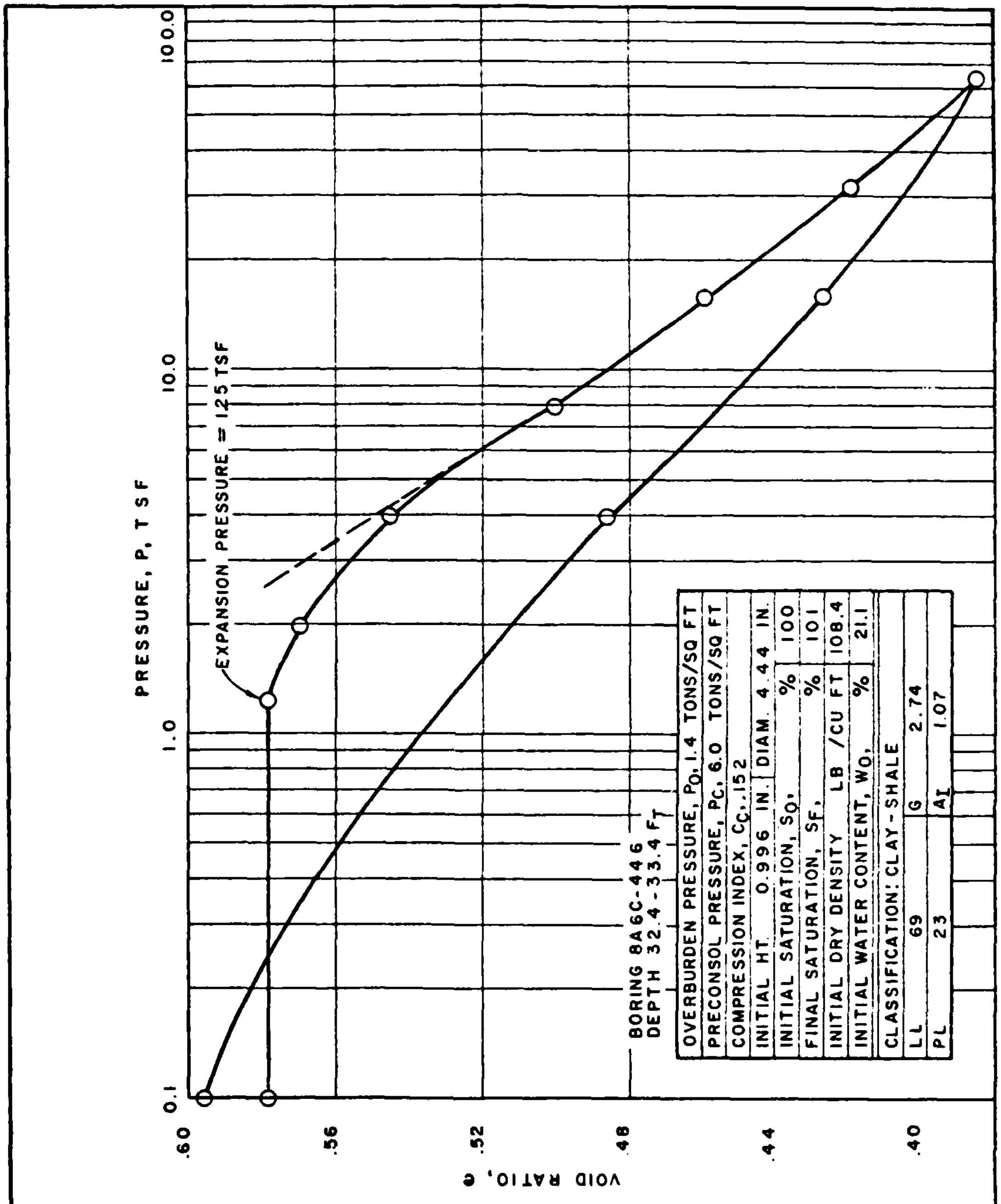
* Plates of Appendix A are on microfiche and have been inserted in a pocket at the back of the report.



SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES - 529

CONSOLIDATION TEST
UPPER PEPPER SHALE - HIGH A_I

US ARMY ENGINEER DISTRICT, FT WORTH

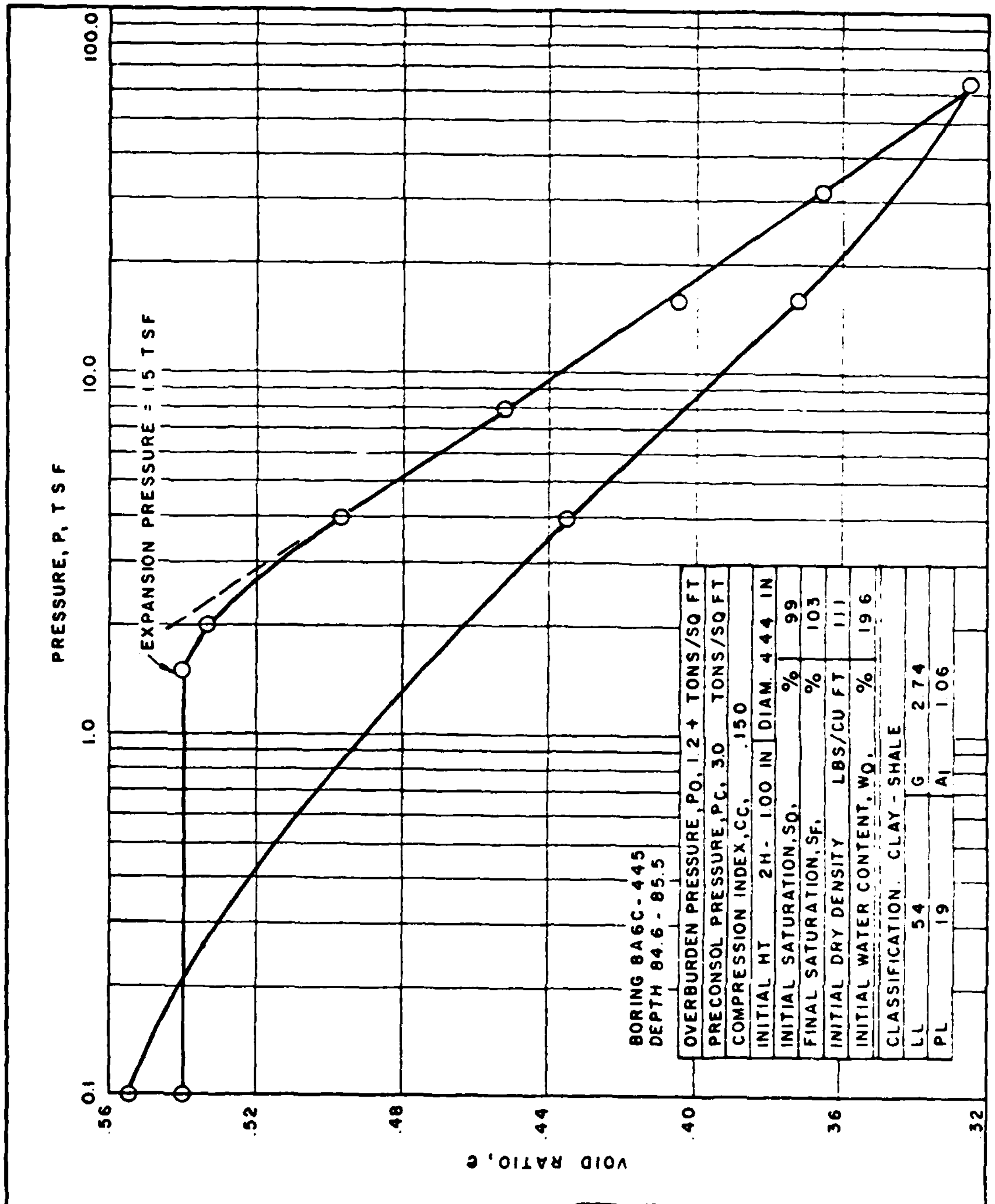


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529

CONSOLIDATION TEST
UPPER PEPPER SHALE - LOW A_I

US ARMY ENGINEER DISTRICT, FT WORTH

PLATE 14

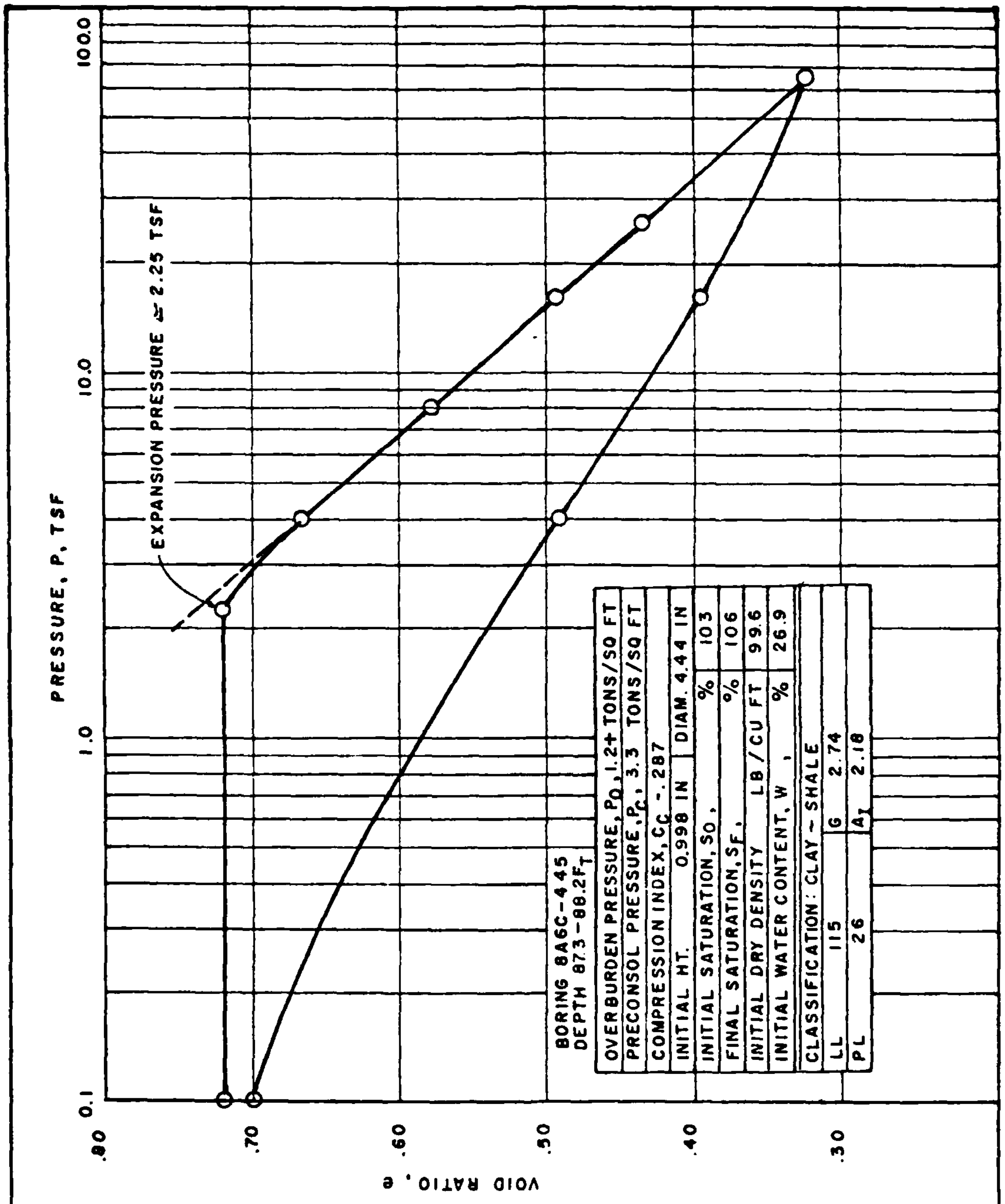


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES - 529

CONSOLIDATION TEST
LOWER PEPPER SHALE

U S ARMY ENGINEER DISTRICT, FT WORTH

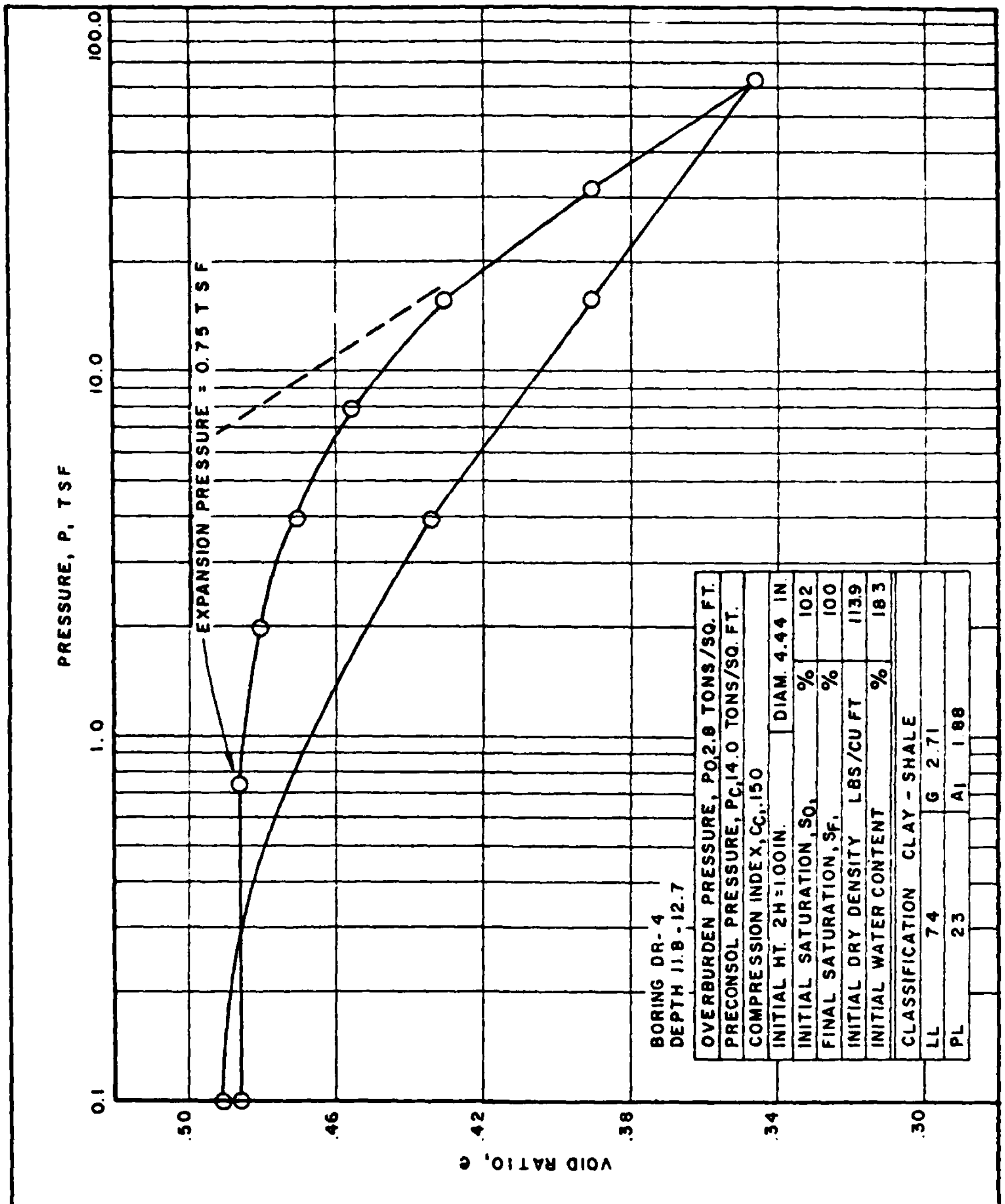
PLATE 16



SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES - 529

CONSOLIDATION TEST
LOWER PEPPER SHALE - HIGH A_I

U S ARMY ENGINEER DISTRICT, FT WORTH

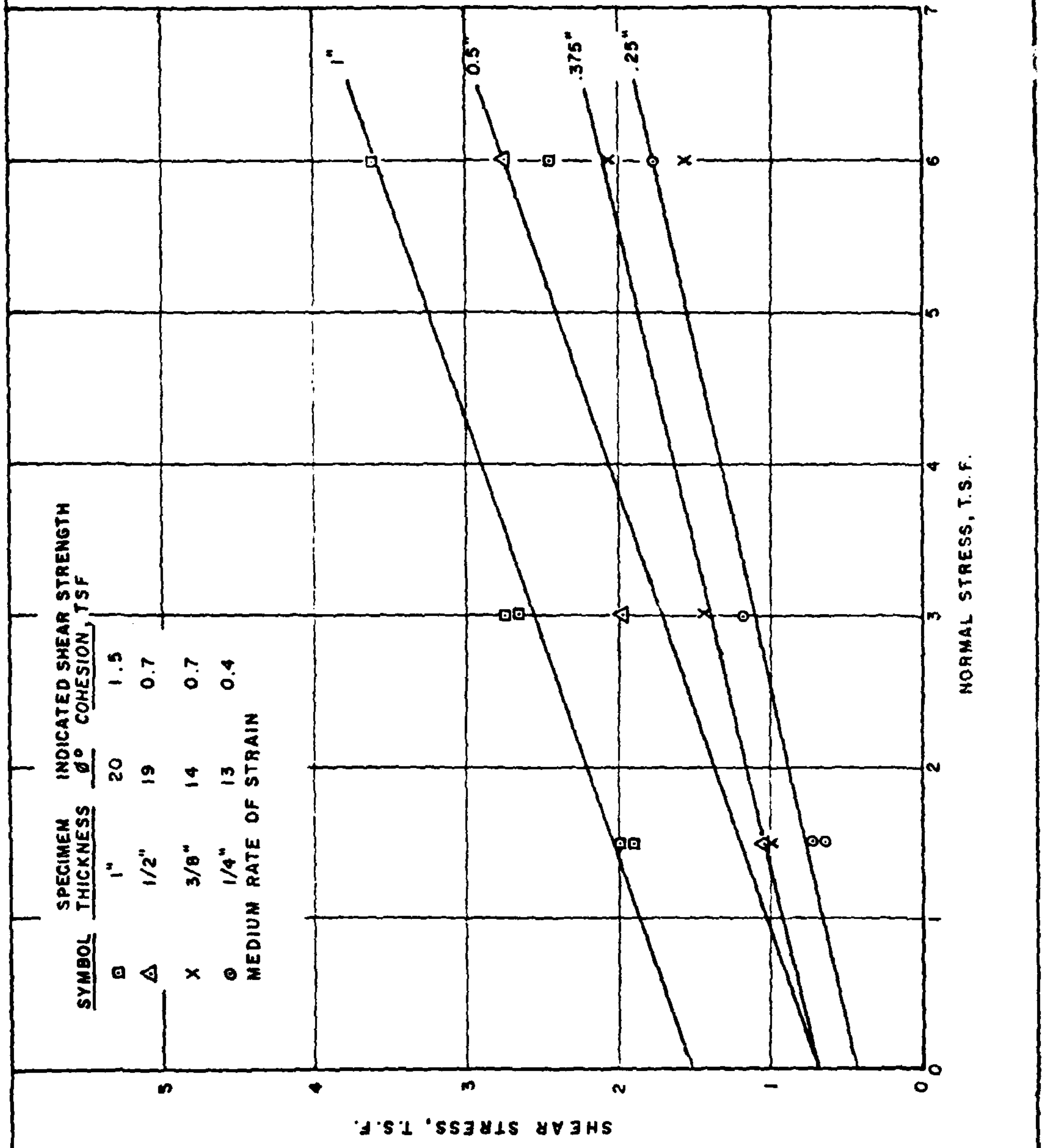


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES - 529

CONSOLIDATION TEST
DEL RIO SHALE

U S ARMY ENGINEER DISTRICT, FT WORTH

PLATE 17

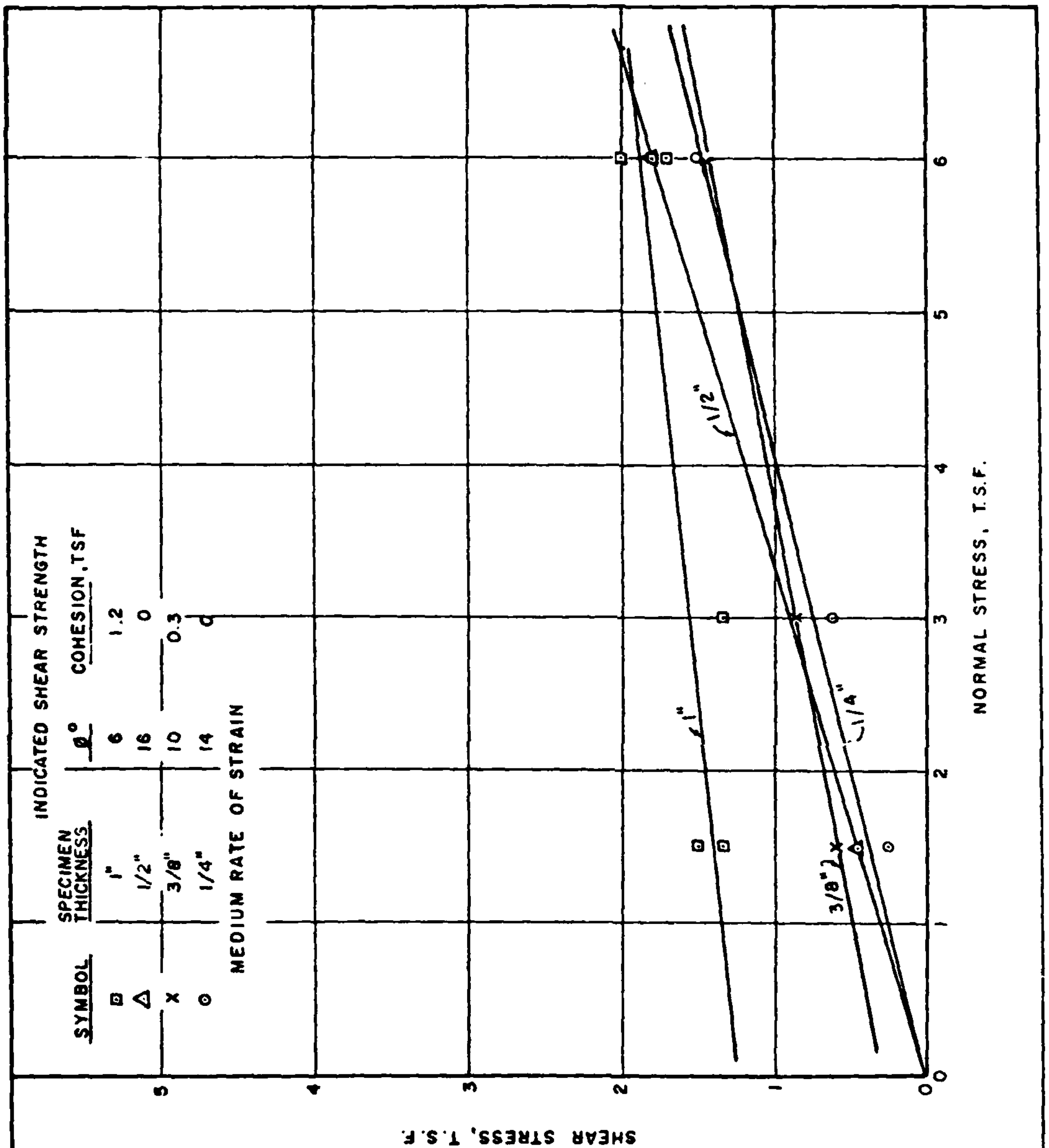


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

UPPER PEPPER SHALE
SHEAR STRENGTH
SPECIMEN THICKNESS

U.S. ARMY ENGINEER DISTRICT, FT. WORTH 1968

PLATE 18

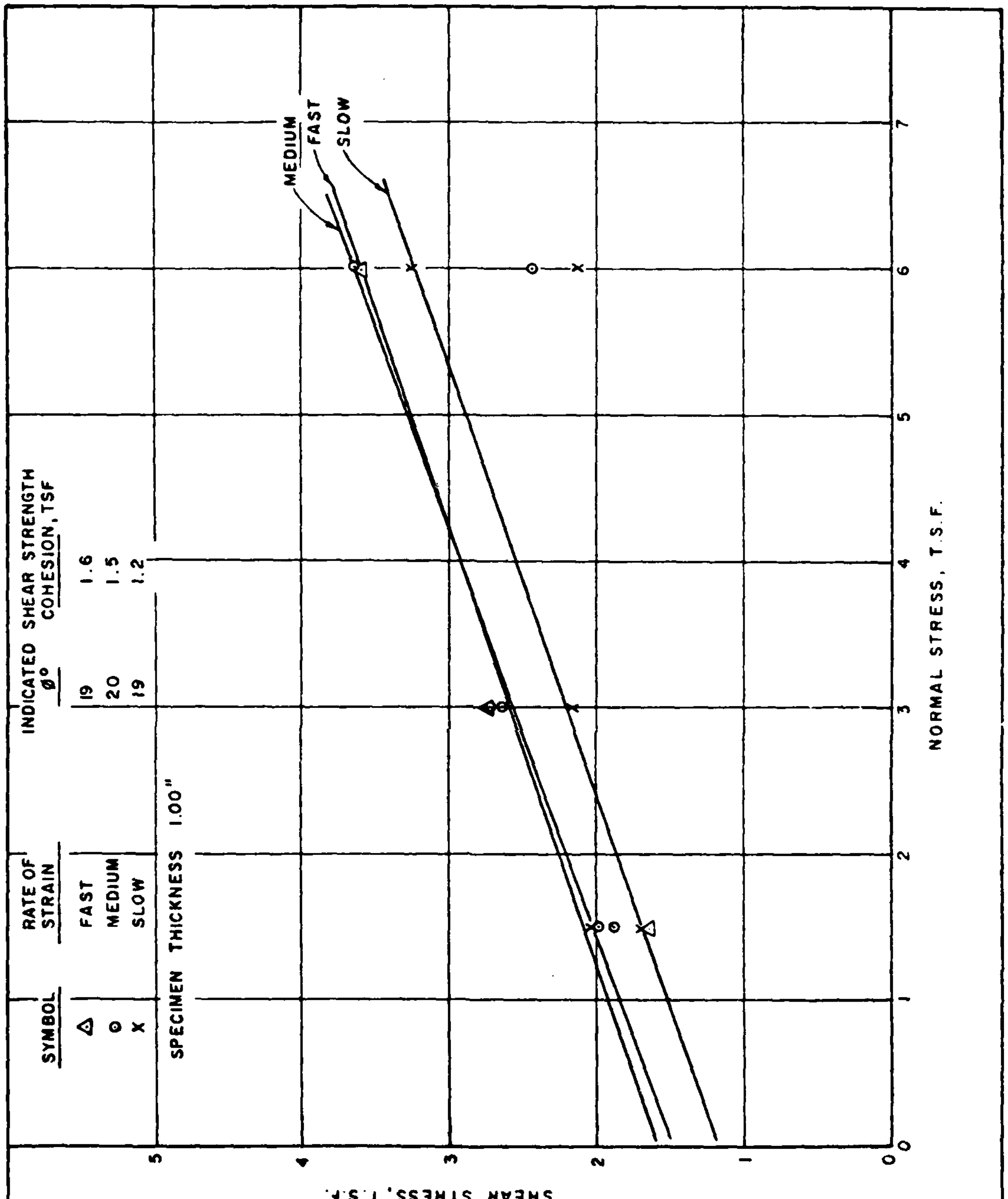


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

LOWER PEPPER SHALE
SHEAR STRENGTH
SPECIMEN THICKNESS

U.S. ARMY ENGINEER DISTRICT, FT. WORTH 1968

PLATE 19

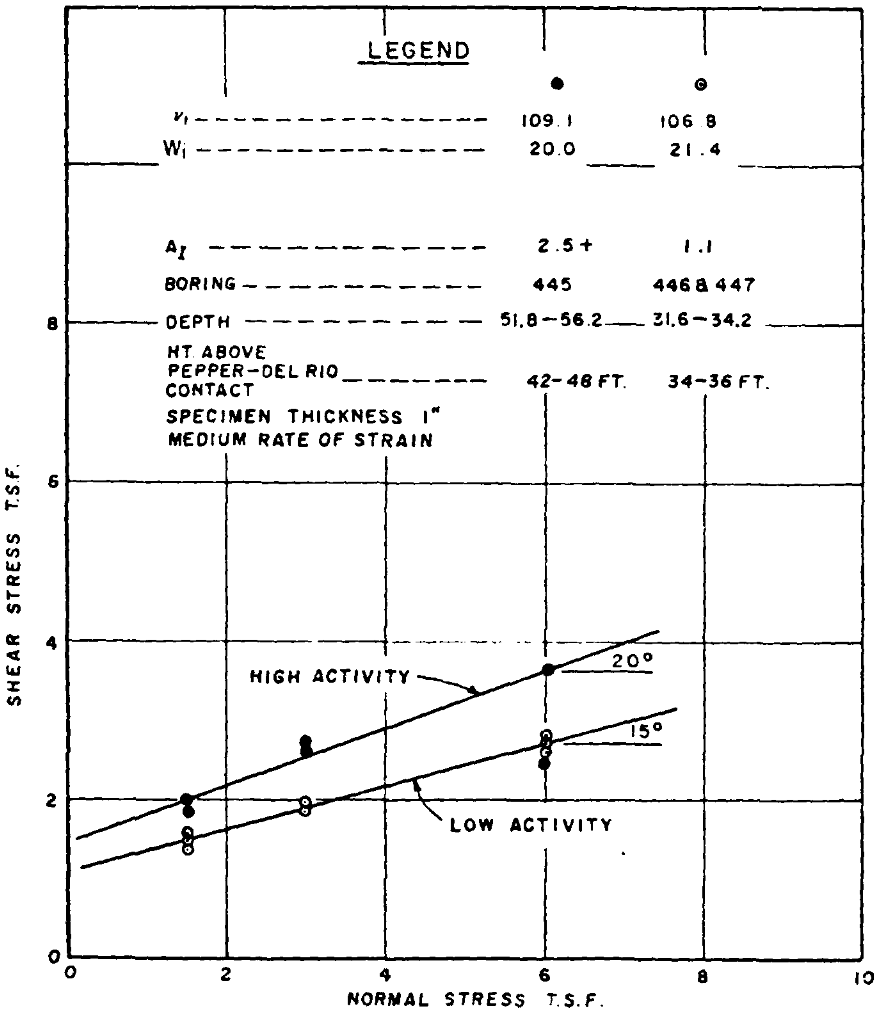


SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES-529

UPPER PEPPER SHALE
SHEAR STRENGTH
RATE OF STRAIN

U S ARMY ENGINEER DISTRICT, FT. WORTH 1968

PLATE 20



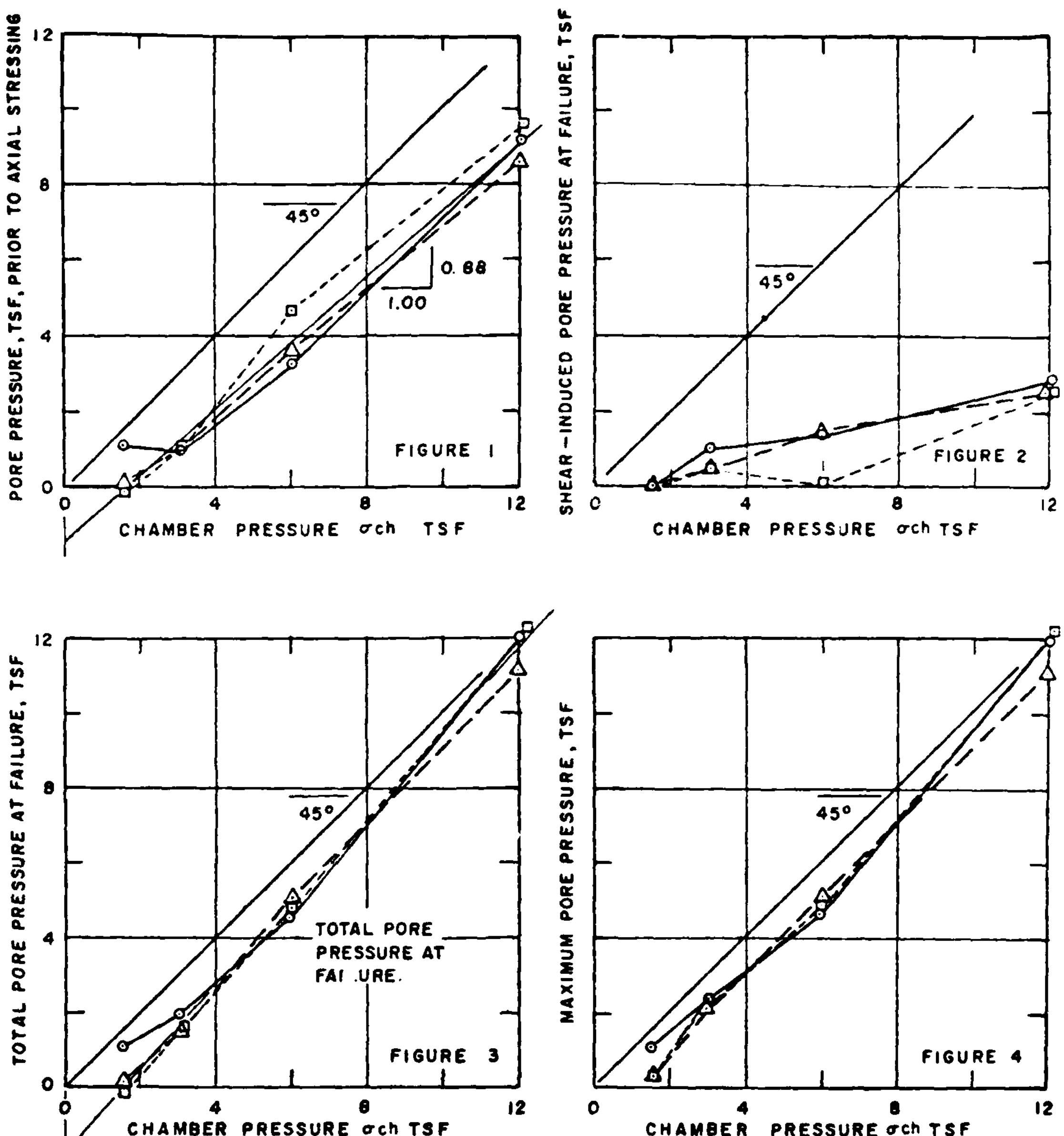
SHEAR STRENGTH CHARACTERISTICS
OF
CLAY-SHALE FOUNDATIONS
ES – 529

UPPER PEPPER SHALE

SHEAR STRENGTH-ACTIVITY INDEX

US ARMY ENGINEER DISTRICT, FT WORTH 1968

PLATE 21

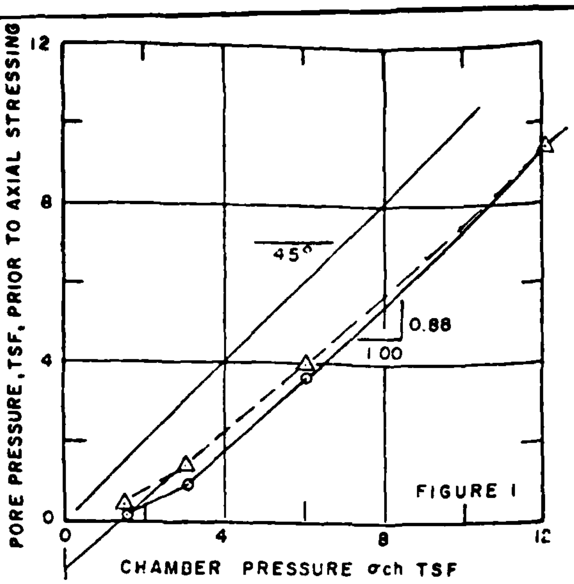


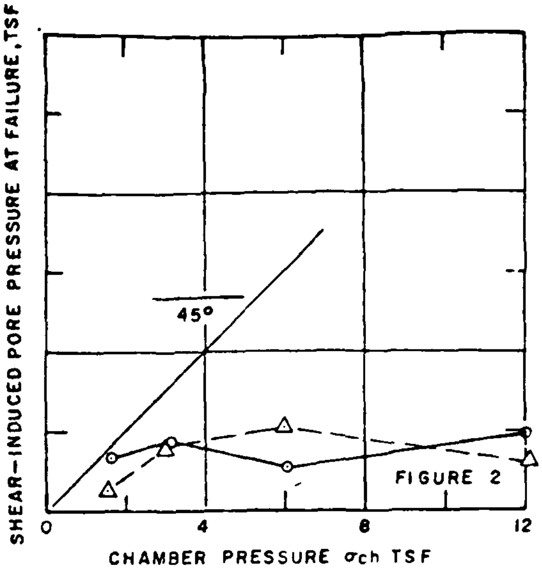
RELATION OF CHAMBER PRESSURE TO PORE PRESSURE

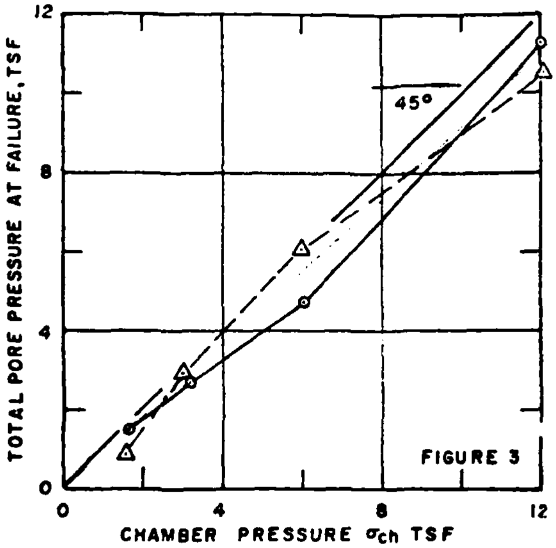
LEGEND

o—o 60° ORIENTATION
Δ—Δ 45° ORIENTATION
□---□ 45° ORIENTATION

Qn TESTS







RELATION OF CHAMBER PRESSURE TO PORE PRESSURE

Qss TESTS

SHEAR STRENGTH CHARACTERISTICS
OF
CLAY SHALE FOUNDATIONS
ES-529

TRIAXIAL COMPRESSION TESTS
UPPER PEPPER SHALE

U.S ARMY ENGINEER DISTRICT, FT. WORTH

PLATE 23